

EUSTACHIAN TUBE FUNCTION IN AVIATION

AN EXPERIMENTAL STUDY IN MAN

by Peter Groth

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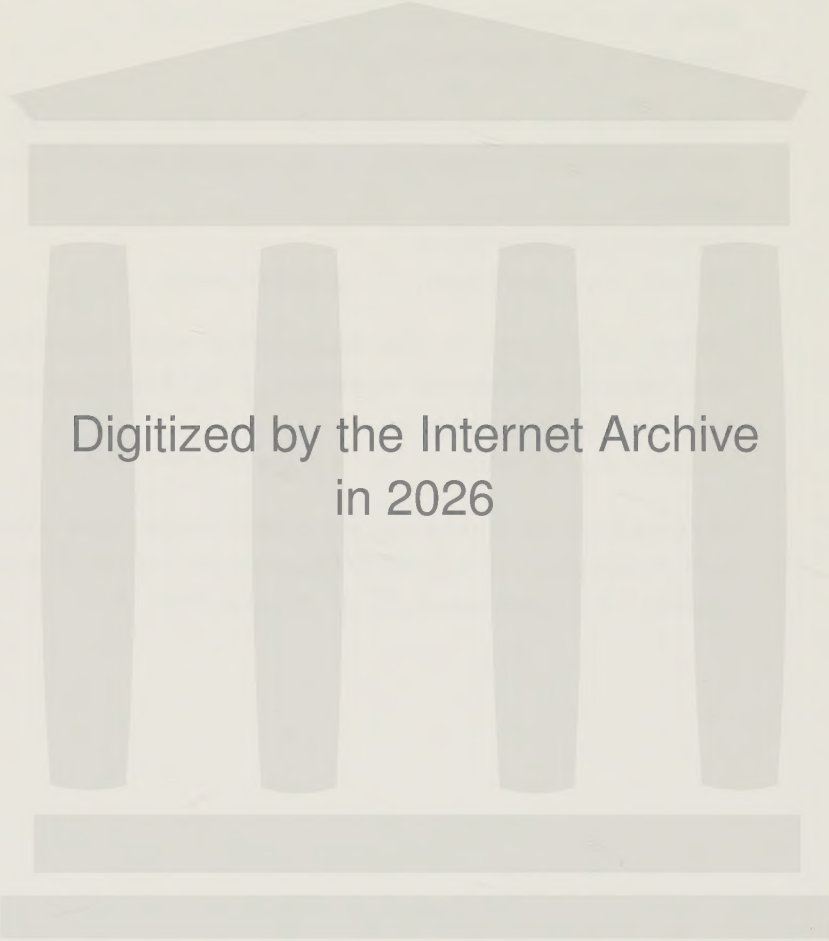
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This thesis is based on the following papers which in the text will be referred to by their Roman numerals:

- I. Eustachian tube function in selection of airmen.
Aviat. Space Environ. Med. 51(1):11-17, 1980.
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- II. Effects of different body positions on the Eustachian tube function in the selection of airmen.
Aviat. Space Environ. Med. 51(9):913-917, 1980.
(Groth, P. & Tjernström, Ö.)
- III. Comparison of Eustachian tube function measured by the microflow method and a new quantitative impedance method.
Submitted for publication.
(Groth, P., Ivarsson, A. & Tjernström, Ö.)
- IV. Effect of flight on the Eustachian tube function and the tympanic membrane system - a follow-up study.
Submitted for publication.
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- V. Reliability in tests of the Eustachian tube function.
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GENERAL INTRODUCTION

One of the fundamental functions of the Eustachian tube is to keep the middle ear pressure equal to the ambient pressure. Continuous gas absorption by the mucous membranes of the middle ear normally creates a small and symptomless pressure gradient across the eardrum. This gradient is equilibrated when the normally closed tube opens, usually by the muscular activity involved in swallowing and jaw movements. If the tube should not open for a longer period of time, the middle ear pressure gradually decreases, causing impairment of hearing, retraction of the eardrum, and eventually maybe even middle ear disease. Consequently normal hearing and a normal eardrum seem to reflect a normal tubal function. This statement may be valid for terrestrial activities, but in aviation with often major and rapid changes in the atmospheric pressure, the strain put on the pressure equilibrating capacity of the Eustachian tube is more serious. Many of us have experienced aural discomfort in flight, especially during descent, despite the fact that we normally have no ear problems and that the rate of change in cabin altitude of commercial aircraft is kept at approximately 100 m/min in order to avoid difficulties connected with pressure equilibration. This is nevertheless the most common complaint made by passengers in civilian aviation (2). Even in military aviation, where the aircrew members are required to have normal tubal function, difficulties connected with pressure equilibration is a grave problem and one of the commonest reasons why pilots are barred from flight duty, i.e. grounded.

The capacity to equilibrate during sudden changes in ambient pressure depends on how frequently the subject can open the tube and how long it remains open. The dimensions of the narrowest part of the tube are also of importance. This capacity also seems to be dependent upon the amount and rate of pressure change. Generally it may be said that the higher the rate of pressure change, the greater the difficulties in equilibration.

During ascent the decreasing atmospheric pressure causes a relative overpressure in the middle ear that moves the eardrum laterally, gives a sensation of fullness in the ear and eventually forces the tube open, passive equilibration. The intratympanic

pressure is instantly reduced as air escapes through the tube, and the sensation of fullness in the ear disappears as the drum moves inwards again. When the pressure in the middle ear is reduced in this way, the tube closes and the cycle is repeated as long as the ascent is continued. There is generally no trouble during the ascent despite the fact that airmen usually do not actively open their tubes during this stage of the flight. However, some 10-17 % of airmen have reported episodes of vertigo at this stage (8,13,14). This has been shown experimentally to be due to a high level of overpressure in one ear as an effect of asymmetric passive equilibration (10).

During descent on the other hand, the increasing atmospheric pressure causes a relative underpressure in the middle ear, but now the tube does not open passively as it does during ascent. Pressure equilibration is brought about when the tube is opened by deglutitions and/or jaw movements. This activity is not sufficient to overcome the pressure difference across the eardrum if the difference is allowed to become too great. Air has then to be forced through the tube, for instance by blowing against the closed nose. If not even this manoeuvre opens the tube, continued descent further increases the pressure difference, causing a traumatic inflammation in the middle ear, usually called aerotitis media (1). The symptoms - pain, temporary impairment of hearing, and sometimes vertigo - depend on the duration, frequency and severity of the trauma. Reduction of these symptoms can only be accomplished by ascent or a rupture of the eardrum which promptly lowers the pressure gradient (1). Such symptoms are of major importance not only because they affect the capacity of the aircrew, but because they occur during the descent, which often requires specific manoeuvres which demand the concentrated attention of the crew, as for instance during landings. Hearing impairment makes radio communication more difficult. This may be of vital importance especially during landing, when contact with the ground is necessary. A misunderstanding at this stage may prove fatal since military aircraft usually have a limited safety margin due to fuel shortage when landing.

There is an economic side to these problems as well. Aerotitis media usually requires several days to heal and the aircrew member affected should be barred from flight duty during

this time. Since training of airmen is so expensive, temporary and above all permanent grounding of a pilot with recurrent aerotitis means a considerable economic loss. It is therefore imperative that effective selection procedures before flight training should be used to detect any condition in the applicant that might impair the pressure equilibrating capacity. The high incidence of groundings, temporary or permanent, due to ear problems in airmen suggests that the indirect and qualitative methods to evaluate the Eustachian tube function used so far have not been adequate. This complex function can obviously be assessed only during simulated ascents and descents in a pressure chamber using a quantitative physiologic method, as described in the present study.

AIM OF THE PRESENT STUDY

To make a comprehensive evaluation of the pressure equilibrating capacity of the Eustachian tube in applicants accepted for flight training in the Swedish Air Force;

to study the reliability in the various measurements of the tubal function by repeated investigations;

to study the effect of flight training on the pressure equilibrating capacity and the tympanic membrane system in repeated investigations during the flight training;

to evaluate the results and their usefulness as a more effective means in the selection of airmen.

EARLIER METHODS USED TO EVALUATE THE PRESSURE EQUILIBRATION CAPACITY OF THE EUSTACHIAN TUBE IN THE SELECTION OF AIRMEN

Valsalva's manoeuvre

In the earlier years of aviation the rates of pressure changes presented no problems, but already during World War I aerotitis media became a painful reality. Although the pathogenesis was understood it attracted little interest. However, it was agreed that candidates for flying service should be accepted only if their ears could easily be inflated by the Valsalva manoeuvre, i.e. a substantial expiration against the closed nose that forces air through the Eustachian tube. Considerable over-

pressures can be established in the rhinopharynx and virtually everybody with normal ears can inflate their ears in this way.

Valsalva's manoeuvre has for a long time been a routine for pressure equilibration among pilots and is still a requirement for pilots in some countries. It has been used both as a selective and a therapeutic manoeuvre. It is not reliable, however, unless the ability to perform it is tested under pressure conditions simulating flight. It is also difficult to evaluate the results of the manoeuvre if based on subjects' reports or the movement of the eardrum in an otoscope. Other drawbacks of the method, when used in flight, are that it may induce convulsive syncope in subjects with low G tolerance (6) and subjects susceptible to alternobaric vertigo may experience this during a Valsalva manoeuvre.

The pharyngeal pressure manoeuvre

This test and therapeutic manoeuvre, suggested by Frenzel (9), is more complicated to master, but it opens the tube at a lower naso-pharyngeal pressure as compared to the Valsalva manoeuvre (3). The pressure increase is brought about by a movement of the tongue against the soft palate while the glottis and the nose are closed. Since it involves no forceful expiration, the risks of alternobaric vertigo and syncope encountered in Valsalva's manoeuvre are avoided.

Toynbee's manoeuvre

The manoeuvre is said to be positive when swallowing with the nose closed results in muscular opening of the tube and a simultaneous negative pressure in the rhinopharynx is transmitted to the middle ear. It is considered proof of normal tubal function (7,21) and can be performed in about 70 % of subjects with normal ears.

A feature in common to these three manoeuvres is that success is evaluated by otoscopy or auscultation. However, if a minimal and momentary force, just strong enough to open the tube, is used or if the eardrum is stiff, its movement may easily be missed by these methods.

Pressure chamber tests

Dickson et al. (4) tested 1000 aircrew cadets in a pressure chamber simulating ascents and descents of 3000 m with a rate of pressure change of 15-20 m/s. The subjects were otologically healthy. They were instructed before the tests to use the Valsalva manoeuvre as a means of equilibration. The tests were run 3 times and after each test the eardrums were examined by otoscopy. 8.9 % complained of symptoms during the tests which were not relieved by Valsalva manoeuvres, and were considered to have failed in the test. However, 28 % had otoscopic evidence of barotrauma. Munker (15) used a differential manometer attached to the ear canal to assess the pressure equilibrating capacity during pressure chamber flights. The method could record eardrum movements caused by tubal openings, but no quantitative information of the pressure equilibrating capacity was achieved.

Auditory canal - middle ear pressure equilibrating methods

A positive or negative middle ear pressure is established through the rhinopharynx. After equilibrating manoeuvres, the residual pressure in the middle ear is assessed by the pressure in the auditory canal needed to move the eardrum into the neutral position, which is determined by otoscopy (21) or by the impedance method (17). The impedance method was tested in both normals and subjects with clinically identified malfunction of the Eustachian tube. Because of overlapping results between groups, the method was considered not suitable for screening purposes.

MATERIAL AND METHODS

All subjects tested were accepted applicants for flight training. Only subjects without a history of a recent upper respiratory tract infection and normal findings at ENT-examination including otomicroscopy with Siegle's test and audiography (within 20 dB ISO, 1964) before all test sessions were accepted.

All test procedures in this study were approved of by the committee for Ethics, University of Lund.

The methods used to record the pressure equilibrating capacity have been described in the individual papers, and only the main

points will therefore be summarized.

The reason for using two methods in this study is that method I, the microflow method, originally meant for basic research work on middle ear mechanics, is complicated and time-consuming and not intended for routine investigations. Method II was designed in the course of the study to overcome these drawbacks and to offer a simplified means to assess the pressure equilibrating capacity in routine investigations.

Method I

The microflow method involves the use of an apparatus consisting of a flowmeter hermetically connected to the bony part of the ear canal by a catheter and in open communication with the ambient pressure at the other end. Movements of the eardrum causes an airflow through the catheter and flowmeter. The flow signal is integrated with respect to time and the volume displaced by the drum movement is recorded. If the eardrum movement is caused by pressure changes in the middle ear only, the recording is correct, but if changes in the ambient pressure are added, they also cause an airflow due to expansion or compression of air in the catheter and ear canal and the flowmeter records the sum of flows caused by these components. In order to isolate the signal caused by eardrum movements, a reference flowmeter with identical volume as the ear flowmeter is used. During changes in ambient pressure the difference in the signals from the flowmeters represents the airflow caused by the eardrum movements only. The signal is integrated and the volume of air displaced by the eardrum is recorded (Fig. 1, paper I).

Method II

The quantitative impedance method continuously records changes in eardrum compliance in relation to maximum compliance during changes in the ambient and middle ear pressures. An earprobe connected to a headset containing a loudspeaker and a microphone was used to introduce and read the sound pressure in the ear canal. A servosystem keeps the sound pressure at a constant level independent of changes in ambient or middle ear pressures. A calculating unit records the volume of the ear canal between the eardrum and the probe as well as changes in this volume

caused by changes in the eardrum compliance. From this recording it is possible to isolate the eardrum compliance. For an accurate isolated recording of the change in compliance any change in the enclosed volume of the external ear canal caused by the earprobe or by the blood content of the skin in the external ear canal is prevented since the pressure in the external canal is changed simultaneously with the chamber pressure via the pressure release conduit of the loudspeaker (Fig. 1, paper V).

Performance

The tests were performed in the seated and the recumbent positions. Ascents and descents were simulated in a pressure chamber by pressure changes of 100 cm H₂O (~ 10 kPa) in 25 s. The following tests were performed.

1. Valsalva's manoeuvre
2. Toynbee's manoeuvre

These manoeuvres were considered positive when the recording indicated movement of the eardrum.

3. Active equilibration of static pressure differences across the eardrum after an increase or decrease in chamber pressure of 10 cm H₂O (~ 1 kPa). Depending upon the results of equilibration of both over- and underpressures, the subjects were distributed among tubal function groups described by Elner et al. (7).
4. The change in chamber pressure required to induce an overpressure in the middle ear that forces the tube open is called the pressure opening level (Pol) (Fig. 1, paper I). The residual overpressure in the middle ear when the tube closes after the pressure opening is called the pressure closing level (Pcl).
5. Active equilibration of dynamic pressure differences across the eardrum as the chamber pressure was raised from -50 to +50 cm H₂O (~ -5 to ~ +5 kPa) in 25 s. During this simulated descent, the subjects were told to do their utmost to equili-

brate using deglutitions and/or jaw movements. The mean deviation of the eardrum from its neutral position (V_{tm} mean) during descent was calculated planimetrically from the V_{tm} curve. The pressure change (P_{tm} mean) required to produce the V_{tm} mean is derived from the P_{ch} curve (Fig. 1, paper I).

6. The residual pressure in the middle ear immediately after descent causes a deviation of the eardrum from its neutral position (V_{tmR}) and the pressure change (R) required to regain the neutral position is derived from the P_{ch} curve and is provided as the percentage of the total pressure change in the chamber.
7. The volume deviation of the eardrum (V_{tm}) was determined in response to changes in chamber pressures of ± 15 cm H_2O ($\sim \pm 1.5$ kPa) (Fig. 2, paper III).

STATISTICAL METHODS

The significance of differences in the results of paired comparisons in single ears as concerns test position and method used was evaluated by Student's t-test.

Analysis of variance was used in the follow-up study (paper IV) for comparisons of results in single ears of the three measurements. The significance of differences between single measurements in the follow-up study was evaluated by the method of simultaneous confidence intervals. Analysis of variance was also used for comparison of results in single ears in the repeated measurements (papers III and V).

The significance of differences in the distribution of single ears in tubal function groups of the three measurements in the follow-up study was evaluated by Friedman's method.

The test-retest reliability of measurements including both methods (I and II) presented as standard deviation ($\overline{SD}$) was assessed as follows: the pooled estimate of the variance was computed by first obtaining the variance of measurements in each ear. Then the square root for the mean variance for all ears was calculated. The standard error of the difference between two measurements was determined according to the formula $\sqrt{\overline{SD}^2 + \overline{SD}^2}$.

For the statistical work, the Department of Statistics, Malmö General Hospital, Malmö, has been consulted.

RESULTS AND COMMENTS

Differences in the number of ears accounted for in the various tests are due to failures in recordings caused by ears with tuba aperta, artifacts in equilibrating manoeuvres and technical errors.

Test-retest reliability

Knowledge of the precision in measurements of the Eustachian tube function in single ears is of importance both for evaluation of the result of a single measurement in a selection procedure, and for evaluation of changes in results during flight training. The precision or test-retest reliability, provided as the standard deviation ($\overline{SD}$) determined from three measurements by method I was for Pol 3.41 cm H₂O, for Ptm mean 3.03 cm H₂O, for R 7.98 % and for Vtm/ $\pm$ 15 cm H₂O 0.81 μ l (paper III). The standard error of the difference between 2 measurements was for Pol 4.82 cm H₂O, for Ptm mean 4.29 cm H₂O, for R 11.29 % and for Vtm/ $\pm$ 15 cm H₂O 0.92 μ l (paper IV). The standard deviation determined from 10 measurements by method II was for Pol 3.55 cm H₂O, for Ptm mean 2.78 cm H₂O, for R 10.79 % and for the residual pressure after equilibration of static overpressures 0.95 cm H₂O and for underpressures 0.88 cm H₂O.

Changes larger than the standard error are presented as improvements or deteriorations of tubal function.

In a comparative study 25 subjects were tested with both method I and method II. The results in the various tests; Pol, Ptm mean, R and static pressure equilibrating capacity did not differ significantly between methods. The standard deviations of different variables were almost equal for both methods (paper III). Since method II can be handled by a technician without assistance and tests are made with a considerable gain of time in comparison to method I, the new method may be considered superior for this purpose.

Valsalva's manoeuvre

All except a few subjects (95 %) mastered the manoeuvre in the seated position (paper I). This is in agreement with earlier investigations of applicants for flight training (3,20). Of the 104 ears tested in both positions, 2 ears were negative in the

seated and 3 in the recumbent position (paper II). In the retests (paper IV) all could perform the manoeuvre. This capacity tells us nothing of the subjects' ability to equilibrate by deglutitions and jaw movements in flight, and is therefore not useful as a selection method. The use of Valsalva's manoeuvre as a means of equilibration has been recommended since the early days of aviation. However, as the performance and efficiency of aircraft have increased and the aircrews' tasks have become more exacting, the method cannot be recommended as a routine to clear the ears. The drawbacks are the risks of alternobaric vertigo and of convulsive syncope in susceptible individuals, and the fact that it requires the help of a hand and access to the nose, and most often during descents, when attention is needed elsewhere. However, it may be useful if other means of equilibration should prove ineffective.

Toynbee's manoeuvre

The manoeuvre was positive in 81 % of the ears in the seated and in 69 % in the recumbent position (paper II). These results are in good agreement with other normal materials (7,18,21). In the follow-up study (paper IV) an obvious improvement was found after flight training. 98 % of the ears tested in the seated and 90 % in the recumbent position were positive. A positive Toynbee's manoeuvre is usually considered evidence of normal tubal function. Elner et al. (7) found a very strong relation between the capacity to equilibrate static pressure differences across the eardrum and a positive Toynbee's manoeuvre. In the present study, however, there were Toynbee negatives who could equilibrate completely during simulated descent and also Toynbee positives who could not equilibrate at all. A positive Toynbee manoeuvre can therefore not be recommended for selection purposes.

Equilibration of static over- and underpressures of 10 cm H₂O

As many as 17 subjects (20 %) could not equilibrate underpressures at all using 10 deglutitions within 3 minutes. If jaw movements were also allowed, 28 ears in 18 subjects improved (paper I). This stresses the importance of the equilibration method used. In the follow-up study (paper IV) there was no significant change in distribution among tubal function groups.

Pressure opening level (Pol)

The mean Pol in 159 ears tested in the seated position (paper I) was 42.8 cm H₂O and is in agreement with earlier investigations (7,19). In the case of the 104 ears tested in different body positions (paper II) the mean was 40.4 in the seated and 54.3 cm H₂O in the recumbent position. For the 32 subjects in the follow-up study (paper IV) there was a mean reduction of 14.2 cm H₂O for the values of Pol in the seated and 11.8 cm H₂O in the recumbent position. The differences in results between body positions and between tests in the follow-up study were both highly significant. 37 ears in the seated and recumbent positions respectively had reduced values of Pol, and 6 and 4 ears respectively had increased values. Especially high values of Pol showed a more marked decrease after flight training.

In the first test (paper I) 3 subjects complained of vertigo at repeated simulated ascents. In all 3 cases there was an asymmetric equilibration of the middle ear pressure with a unilateral Pol above 60 cm H₂O. The symptoms were defined as alternobaric vertigo, and all 3 discontinued their flight training, 2 of them because of recurrent episodes of alternobaric vertigo and 1 for non-medical reasons.

The mean pressure across the eardrum during descent (Ptm mean)

The mean of Ptm means in 162 ears examined in the seated position was 14.8 cm H₂O (paper I). In the case of the 104 ears tested in both body positions (paper II), the mean of Ptm means was 14.2 in the seated position and 19.1 cm H₂O in recumbency. The difference in results between body positions was highly significant. This variable was tested on 3 different occasions during the flight training and there were no significant changes of Ptm mean except in recumbency, where a mean lowering of 3.7 cm H₂O was seen (paper IV). Repeated measurements of Ptm mean showed a very good reproducibility (paper V). The relationship between Ptm mean and pressure equilibrating capacity is not simple to evaluate. It seems reasonable that subjects with a very good equilibrating capacity should have a low value of Ptm mean. However, some subjects claim that they have to allow the pressure across the eardrum to grow until they feel the load. Only then can they equili-

brate. This is illustrated in Fig. 6 (paper I) where the mean ± 1 SD for Ptm mean in subjects with no residual pressure in the middle ear after descent (R_0) is above 17 cm H_2O .

Residual pressure in the middle ear immediately after descent (R)

In the 84 subjects tested in the seated position (paper I), 46 (55 %) had no residual pressure in their middle ears after descent, i.e. they were able to equilibrate completely. In the 52 subjects tested in both body positions (paper II), 54 % in the seated and 31 % in the recumbent position could equilibrate completely. There was a fairly good correlation between Ptm mean and the residual pressure as seen in Fig. 6 (paper I).

This variable was tested on 3 different occasions during the flight training (paper IV) and although there were no significant changes in results between the measurements, a tendency towards lower mean values was seen. The reliability in measurements of R was relatively poor and most probably caused by the fact that ears with large residual pressures mixed good and poor performance while those with low residual pressures showed a high reliability (paper III). Of the 61 subjects who could equilibrate the static pressure differences completely by the method of free choice, only 45 could equilibrate completely during dynamic pressure changes (Fig. 5, paper I). These results indicate that it is not possible to identify subjects who will undergo simulated descents without residual pressure in the middle ears by their results in the static pressure equilibration test. The results also indicate that it is more difficult to equilibrate dynamic pressure changes, and that such tests therefore are the more decisive.

$$V_{tm}/\pm 15 \text{ cm } H_2O$$

This variable was tested on 3 different occasions during the flight training with a significant increase in Vtm between all 3 tests (paper IV). Ears with a low Pol had no significant increase in Vtm in contrast to ears with a high Pol. There was, however, no relation between the value of Ptm mean and changes in Vtm. It was thought that the Vtm might be an objective check of the equilibrating capacity of the Eustachian tube with a strong relation between increase in Vtm during flight training and poor

function. The wide range of $V_{tm}/\pm 15$ cm H₂O already before flight training indicated individual differences which make changes in V_{tm} during flight training difficult to evaluate. Even subjects with a perfect equilibrating capacity during descent had a significant increase in V_{tm} during flight training.

For most variables tested there was an asymmetry between ears in some subjects. This means that both ears must be tested in every subject, since the subject's capacity is decided by the ear with the poorer function (Tables IV and V, Fig. 8 in paper I).

GENERAL DISCUSSION

The comprehensive mapping out of the pressure equilibrating capacity of the Eustachian tube showed a wide range in the results despite the apparent otological uniformity of the material. The asymmetry in tubal function between ears in the same subject that was found, makes it necessary to test both ears in every subject to allow the evaluation of the subject's pressure equilibrating capacity. The results of this study emphasize the inadequacy in today's criteria for the selection of airmen. Since the incidence of aerotitis media in fighter pilots has shown an increase parallel to the increase in performance of aircraft (5) the present requirements for tubal function might prove increasingly inefficient and further stress the need for a more effective selection procedure. In an attempt to make the test procedure more decisive the recumbent test position was chosen because it is known to reduce the pressure equilibrating capacity of the tube. This reduction is caused by a venous congestion of the mucous membranes of the tube (16). Since upper respiratory tract infections are common causes of grounding of airmen due to a reduction in tubal function, obviously by a similar mechanism, the recumbent test position gives an opportunity to find out to what extent airmen can equilibrate in recumbency and in this way prove a valuable reserve capacity, that can allow them to fly with a greater margin of safety. The highly significant reduction in pressure equilibrating capacity found in the recumbent position certainly increases the possibilities to select subjects that can undergo pressure changes in the ambient atmosphere without difficulties to equilibrate.

In the follow-up study, the retests after flight training generally confirmed the results from the initial test or showed improvement. These findings together with the results of reliability determinations in the different functions make the initial test results dependable. The risks of picking an applicant with poor tubal function because of a temporarily good test result seems negligible.

However, the validity of the test results lies in a good agreement with the results of the flight training. If we assume that higher rates and amounts of ambient pressure change are more difficult to equilibrate, then subjects who cannot equilibrate during the very moderate pressure changes in the chamber would certainly not be able to do so in flight. However, Frenzel (9) reported that more pilots had equilibration difficulties in the pressure chamber than in flight and stated that the physical and psychic tension of the pilots in flight improved their tubal function. Some of the subjects in this study reported spontaneously that their difficulties in connection with pressure equilibration were greater during the first part of the flight training, when mainly piston-engined aircraft were used, than in later stages when they used high performance fighters. They stated that it was easier to equilibrate in manoeuvres exposing them to high G forces. When the body is exposed to G forces, the blood pressure in the vessels of the head is lowered. This may explain an improvement in tubal function in analogy with the poorer tubal function caused by an increase in the venous pressure in the head in the recumbent position. On the other hand, all except one subject with large residual pressures in the middle ears after simulated descent admitted that they had to use Valsalva's manoeuvre every now and then to equilibrate during rapid descents. Thus, differences in rates and amounts of the pressure change in flight and in the pressure chamber are one reason that makes it difficult to assess the validity of the tests. Since pilots do not generally admit difficulties during flight for fear of being rejected, and since problems connected with pressure equilibration are far from being the only cause of failure, it may be difficult to find out when poor tubal function is the real reason.

Which test or combination of tests should be used in a selection procedure? Normal hearing and normal otoscopic findings are

obviously not sufficient. It has been shown that a positive Valsalva or Toynbee manoeuvre adds little of value in this matter. Subjects who can equilibrate static pressure differences completely can usually also equilibrate dynamic pressure changes. However, of the 61 subjects in this study who could equilibrate static pressure differences completely, only 45 could equilibrate dynamic pressure differences as well. Equilibration of static pressure differences can therefore not be regarded as a satisfactory selective test for this purpose.

Ptm mean mirrors the state of the eardrum during descent, the stage of flight that causes most of the ear problems encountered. Even if a few subjects who can equilibrate completely allow themselves a moderate Ptm mean, it is generally a dependable variable of the pressure equilibrating capacity with high precision in repeated measurements and therefore of great value in the selection procedure. The residual pressure in the middle ear is obviously also an important measure of the wanted qualification, but has a lower precision in repeated measurements. Together these two variables seem to give a complete picture of the subject's capacity to equilibrate during simulated descent.

The pressure opening level during simulated descent should be determined in order to find subjects susceptible to alternobaric vertigo. Subjects with repeated episodes of alternobaric vertigo during tests should obviously be disqualified but in subjects with high unilateral pressure opening level without alternobaric vertigo the possibilities of a reduction of this level during the flight training should also reduce the risks for alternobaric vertigo and therefore maybe not be looked upon as seriously.

Which are the possible effects of flight training on the tubal function? The improvement in results of Toynbee's manoeuvre is obvious, but hardly useful since there was no simultaneous improvement in the capacity to equilibrate during simulated descents except maybe a tendency. The evident decrease of Pol suggests an effect of flight on the tubal wall that may be of importance to avoid risks of alternobaric vertigo since it is predominantly subjects with high values of Pol who show the substantial decreases.

The use of a quantitative method makes it possible to rank the applicants according to their equilibrating capacity. A fixed requirement for acceptance or rejection can also be determined, but

at what levels? The most decisive test, to equilibrate completely during descent in the recumbent position was managed by 30 % of the applicants, but a prerequisite for such a tough requirement is a large supply. On the other hand it seems obvious that at least the 8 % of the applicants that could not equilibrate at all during simulated descent, not even in the seated position, should be disqualified regardless of the supply.

With the support of the results achieved in this study and with access to an objective and convenient method, it is the author's opinion that an advanced testing of the pressure equilibrating capacity of applicants for flight training is justified despite the difficulties to actually prove a connection between failures in flight and poor tubal function. However, further studies in this field should comprise tests of the pressure equilibrating capacity at higher rates and amounts of pressure change before basic medical standards of the Eustachian tube function feasible in the selection of applicants for flight training are decided upon. Attempts must be made to find out if and to what extent applicants with poor results in the tests become less useful pilots because of a high incidence of grounding, interrupted training sessions, low mission capacity and fitness for use.

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EUSTACHIAN TUBE FUNCTION IN SELECTION OF AIRMEN

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Abstract. A comprehensive study of Eustachian tube function in 84 aspirants accepted for flight training was made. Using a pressure chamber, both static and dynamic pressure changes, as in ascent and descent, were applied to test the tubal pressure equilibrating capacity in the sitting position. While all 84 were otologically healthy, a wide range in the pressure equilibrating capacity was found - 20 % could not equilibrate static over- and underpressures of 10 cm H₂O completely, 8 % could not equilibrate at all during simulated descent, 3 subjects reported acute vertigo during simulated ascent in combination with high unilateral middle ear pressure. Asymmetry between ears of single subjects in pressure equilibrating capacity was also found to a large extent. It was not possible to identify subjects with poor equilibrating capacity by simple tests like Valsalva's or Toynbee's manoeuvres. The results may indicate that today's criteria for Eustachian tube function in the selection of airmen can be made more efficient.

Difficulty with clearing the ears during flight is a common cause of temporary (1,3), or even permanent, grounding of airmen (4).

Normal tubal function is an indispensable condition for acceptance for flight duty. For most occupations, this function is generally regarded as acceptable if hearing is normal, conventional otoscopic examination reveals nothing remarkable, and the applicant has no history of ear disease. But for airmen, often exposed to large and rapid changes in the atmospheric pressure, the demands placed on the equilibrating capacity of the tubes are more rigorous.

Ascent usually offers no trouble, in spite of the fact that most pilots do not actively clear their ears. This absence of trouble is due to the passive escape from the middle ear of expanding air when the increasing pressure in the middle ear exceeds the closing forces of the tube, and opens it - the so called pressure opening. However, some 10-17 % of airmen have reported episodes of vertigo at this stage (8,13,14). This symptom has been shown to be induced by an asymmetrical equilibration of the middle ear pressures and when the middle ear pressure on one side reaches a certain level (10).

During descent, equilibration is brought about by passage of air into the middle ear, usually by the tubal muscular activity of deglutition and jaw movements. If these manoeuvres are not successful, air can be forced into the middle ear through increasing the pressure in the nasopharynx by the Valsalva manoeuvre, for example.

Failure to equilibrate may result in temporary pain, impairment of hearing, and vertigo, with or without rupture of the tympanic membrane, and can compromise aircraft safety if a member of the crew is incapacitated in this way (1,11,17). The problem is not only a question of flight safety but also one of economical importance. Since training airmen is so expensive, permanent grounding of a pilot means a considerable financial loss (15,19).

Except the usual requirements - normal hearing, normal otoscopic findings and no history of ear disease - Valsalva's and Toynbee's manoeuvres evaluated by otoscopy are often used as tests of the tubal function. However, there is a need for an objective method; to this end Sutherland, Bragg, and Collins (17) used an acoustic impedance bridge to evaluate various tests of the tubal function, but found the procedure unsuitable for

screening purposes.

Evaluation of the tubal function necessary for airmen should be based on their ability to clear their ears during changes in pressure of the ambient atmosphere, i.e. the ability to open the tube actively by various manoeuvres and to do so at a given instant, repeatedly, during a sudden change in pressure. This complex function should obviously be tested during simulated flights in a pressure chamber. Such tests are in use, but the assessments are based mainly on sensations experienced and reported by the test subject. This information may be limited or even misleading since, as known, applicants for flight duty tend to conceal any aural impairment they might have.

Münker (16) described a method for testing Eustachian tube function in a pressure chamber with a differential manometer. However, this method does not give any quantitative information about equilibrating ability.

As early as 1967, Ingelstedt et al. (9) described a method for quantitative evaluation of the pressure equilibrating ability of the tube in intact ears during simulated aviation in a pressure chamber. Elner et al. (6,7) used and modified this method and found the ability to equilibrate small static over- and under-pressures by repeated deglutitions to be poor in 7 % of 102 healthy subjects with normal hearing, normal otoscopic findings, and a negative history of ear disease. Since these 7 % would have filled the criteria often used in the selection of applicants for training as airmen, there is reason to believe that applicants with poorer tubal function are accepted for flight training today. This, together with the frequency and severity of ear trouble during flight (2,4), stresses the need for more objective tubal function tests in the selection of applicants for flight duty.

By means of the method by Ingelstedt et al. (9), modified by Elner et al. (6), for quantitative studies of the equilibrating capacity during ambient pressure changes, a comprehensive study was undertaken in order to evaluate different tubal function tests for subjects with intact eardrums. The aim of the present study was to describe and compare the results of these different tests in applicants accepted for flight training, and to find out whether any of today's criteria can predict a subject's ability to tolerate rapid ambient pressure changes without aural

complications.

This paper is the first in an intended series of investigations of tubal function in aviation.

MATERIALS AND METHODS

The ability of the Eustachian tube to equilibrate the intratympanic pressure during ambient pressure changes was measured with the method devised by Ingelstedt et al. (9), as modified by Elner et al. (6).

The method records the volume of air displaced by the movement of the eardrum in response to changes in the intratympanic pressure and the pressure in the ambient atmosphere. The recording was done with the subject in a pressure chamber, where ascents and descents were simulated by pressure changes of ± 50 cm H₂O (± 4.91 kPa) for 25 s at a constant rate of pressure changes during 80 % of the time. The intratympanic pressure changes caused by the Valsalva and Toynbee manoeuvres were also recorded in this way. A diagram of the recording equipment is given in Fig. 1.

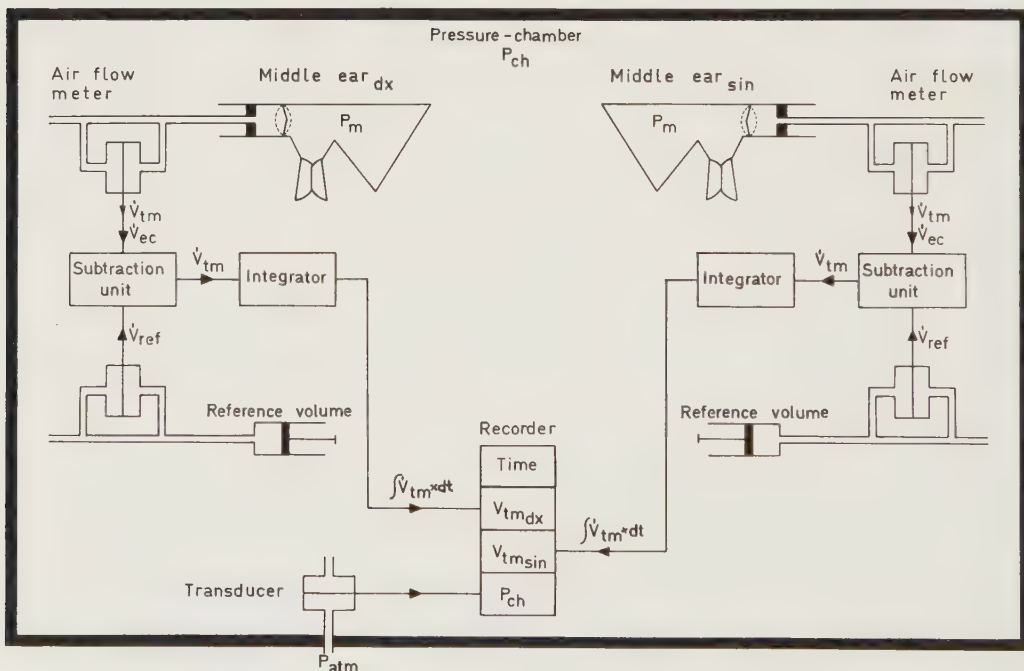


Fig. 1. Equipment used for recording eardrum displacement (V_{tm}) on change of ambient pressure (P_{ch}). For details see text.

A polyethylene catheter was fitted airtight in the bony part of the ear canal. The other end of the catheter was in open communication with the atmosphere of the chamber via a flowmeter. With this arrangement it was possible to record the airflow ($\dot{V}_{tm}$) caused by movements of the eardrum in response to changes in the pressure prevailing in the intratympanic cavity (P_m). However, when the ambient pressure (P_{ch}) was changed, the airflow was the combined effect of drum movements due to middle ear pressure changes and compression or expansion of air in the system ($\dot{V}_{ec}$). The latter component was corrected for by introduction of a reference system ($\dot{V}_{ref}$) operating an identical flowmeter. In the properly balanced system, the signals from $\dot{V}_{ec}$ and $\dot{V}_{ref}$ cancelled out each other, and the resulting signal $\dot{V}_{tm}$ was integrated with respect to time to allow the recording of the volume of air displaced by the movement of the eardrum. A recording of the volume of air displaced by movement of the eardrum and the pressure prevailing in the chamber during simulated ascent is given in Fig. 2.

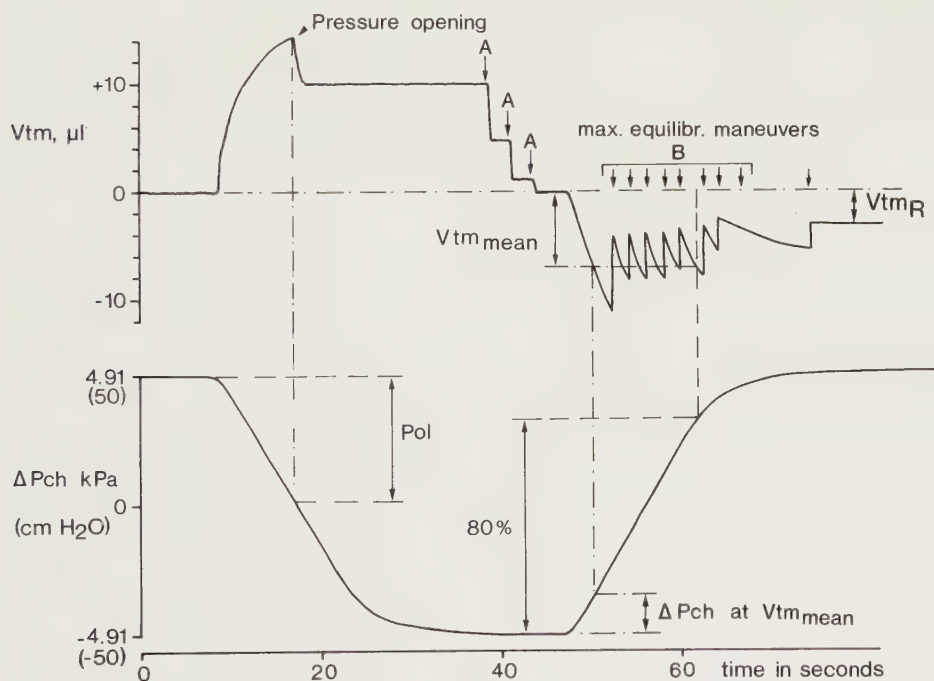


Fig. 2. Example of recording of eardrum displacement (V_{tm} in μl) and chamber pressure (P_{ch} in $\text{cm H}_2\text{O}$ and kPa). Pol. indicates pressure opening level and V_{tmR} indicates the eardrum displacement at residual pressure (R). For details see text.

The rise in the V_{tm} curve demonstrates the gradual bulging of the drum by the increasing relative overpressure in the middle ear, as the P_{ch} is lowered. The sudden drop in the recording was caused by the pressure opening of the tube. The change in the chamber pressure (ΔP_{ch}) necessary to induce this is derived from the P_{ch} curve; it is called the pressure opening level (P_{ol}). Fig. 2 also gives the corresponding events during descent. The drum was brought back to its neutral position by active equilibrating manoeuvres (arrows A). During an increase in the chamber pressure from -50 to +50 cm H_2O (-4.91 to +4.91 kPa), the subject was instructed to equilibrate as frequently as possible (arrows B). V_{tm} mean in the diagram denotes the mean volume of air displaced by movements of the drum from its neutral position during the linear phase of the increase in the chamber pressure. This V_{tm} mean was calculated planimetrically from the V_{tm} curve. The pressure change (ΔP_{ch}) required to produce this V_{tm} mean is derived from P_{ch} curve. The ΔP_{ch} can be used as a measure of the mean pressure gradient across the eardrum (P_{tm} mean) during descent as the difference between ΔP_{ch} and P_{tm} is negligible (10) for the purposes of this study. The residual pressure in the middle ear immediately after descent (R), causes a deviation of the drum from its neutral position (V_{tmR}). R is calculated from the P_{ch} curve. Both P_{tm} mean and R are used as measures of the equilibrating capacity during simulated descent.

Performance: The purpose of the tests was explained to the subject, who was also given instructions and a demonstration of Valsalva's and Toynbee's manoeuvres. The subject was seated comfortably in a pressure chamber. Recordings were made from one ear at a time in the following order:

1. Active equilibration of static pressure differences across the drum after an increase or decrease in the chamber pressure by 10 cm H_2O (0.98 kPa). The subject was then allowed to swallow 10 times within 3 min. The test was repeated, and this time the subject was allowed to equilibrate in any way he wished, including jaw movements, for example, but not Valsalva's or any other manoeuvre requiring the use of a hand. This is called the method of free choice. According to results of each test the subjects were distributed separately among tubal function groups described by Elnor et al. (7). We decided to use this classification in order to allow comparison of the results with those in the normal

material of that work.

- Group I Equilibrates pressure difference across the eardrum completely.
- Group II Equilibrates with small residual pressures in the middle ears.
- Group III Equilibrates a relative overpressure like group II, but does not equilibrate a relative underpressure at all.
- Group I was divided further into subgroups:
- Group Ia Patulous tubes.
- Group Ib Equilibrates completely by 1-3 deglutitions or manoeuvres of free choice.
- Group Ic Equilibrates completely by 4-10 deglutitions or manoeuvres of free choice.

2. Valsalva's manoeuvre: Displacement of air by the movement of the eardrum when the subject made a forceful expiration against the closed nose was recorded as positive.

3. Toynbee's manoeuvre: Displacement of air by the movement of the eardrum when swallowing with the nose closed was recorded as positive. Five tries were allowed for each manoeuvre.

4. Active equilibration of dynamic pressure differences across the eardrum as the chamber pressure was raised from -50 to +50 cm H₂O (-4.91 to +4.91 kPa) in 25 s. During this simulated descent, the subject was requested to do his utmost to equilibrate by the method of free choice. P_{tm} mean was determined as described above and the residual pressure in the middle ear immediately after descent was measured as the percentage of the total pressure change in the chamber. According to the results, the subjects were distributed among four groups:

- Group R₀ No residual pressure in the middle ear (at most 4 %).
- Group R_{≤50} 5-50 % residual pressure.
- Group R_{>50} 41-95 % residual pressure.
- Group R₁₀₀ 96-100 % residual pressure.

5. The pressure opening level (Pol) of the tube was determined during simulated ascent, and during this test the subject was not allowed to equilibrate.

Material: The material consisted of 84 men, aged 17-24 years (mean 20), who had been accepted for training as pilots. Otoscopic examination, including Siegle's test, audiography (within 20dB ISO) had revealed nothing remarkable and none had a history or signs of recent upper respiratory tract infection.

RESULTS

To simplify comparisons with earlier investigations, mainly that of Elner et al. (7), who used the same method but examined only one ear in each subject, we decided to present the findings in individual ears and in subjects separately, and to use Elner's tubal function groups. If the result of a test was poorer on one side than the other, the poorer result was taken as representative of the subject. This usually leads to poorer results for subjects than for single ears.

The results of active equilibration of static relative under-pressure (inhalation) and relative overpressure (exhalation) in the middle ear by deglutition are given in Table I, together with the figures presented by Elner et al. (7). It is seen from the table that 15 % of the ears (20 % of the subjects) are in groups III + IV, i.e. poor equilibrating ability, compared with 7 % in the material of Elner et al. (7). As some of the subjects preferred other means to equilibrate, the test was repeated mainly for the benefit of those who might perhaps be able to improve their performance. This second time they were allowed the method of free choice. Of the 89 ears retested, 28 improved and were upgraded to a better tubal function group. As can be seen from Table II, three ears in Ib were upgraded to Ia, 2 in Ic to Ib, etc. The corresponding figures for subjects are given in the same table. The resulting difference between the distributions of the entire material according to the methods of equilibration are given in Fig. 3.

In 98 % of the ears and 95 % of the subjects, Valsalva's manoeuvre was positive. The corresponding figures for Toynbee's manoeuvres were 80 % and 70 %, respectively. The distribution of the material among tubal function groups is given in Table III.

Table I. Distribution of single ears in tubal function groups by deglutition. Comparison with the material of Elner et al.

	Elner's normal material		our material	
	No.	%	No.	%
Ia	4	4	12	7
Ib	33	32	82	49
Ic	37	36	22	13
II	21	21	27	16
III	2	2	12	7
IV	5	5	13	8

Table II. *Improvement in equilibrating capacity by method of free choice compared with deglutition.*

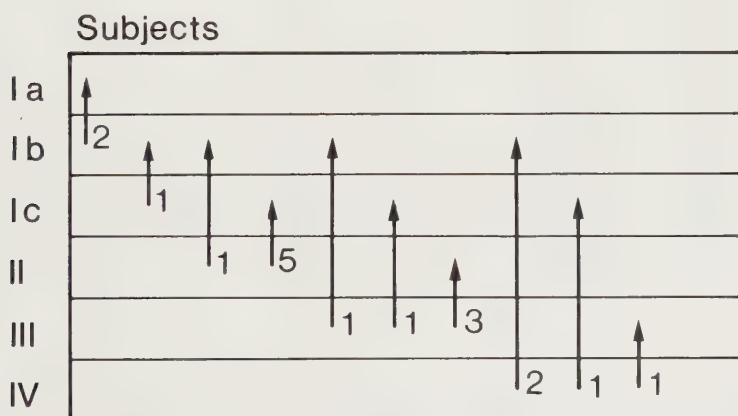
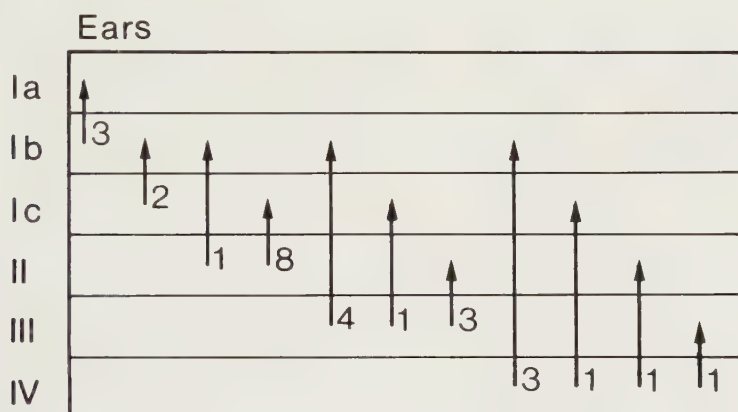


Table III. *Distribution of Valsalva and Toynbee positives among tubal function groups using method of free choice.*

	EARS				SUBJECTS			
	Valsalva		Toynbee		Valsalva		Toynbee	
	No.	%+	No.	%+	No.	%+	No.	%+
Ia	15	100	15	88	5	100	5	100
Ib	84	95	73	84	36	92	30	75
Ic	29	97	24	80	15	94	12	75
II	22	100	14	67	14	100	7	50
III	5	100	3	60	3	100	2	67
IV	7	100	5	63	6	100	3	50

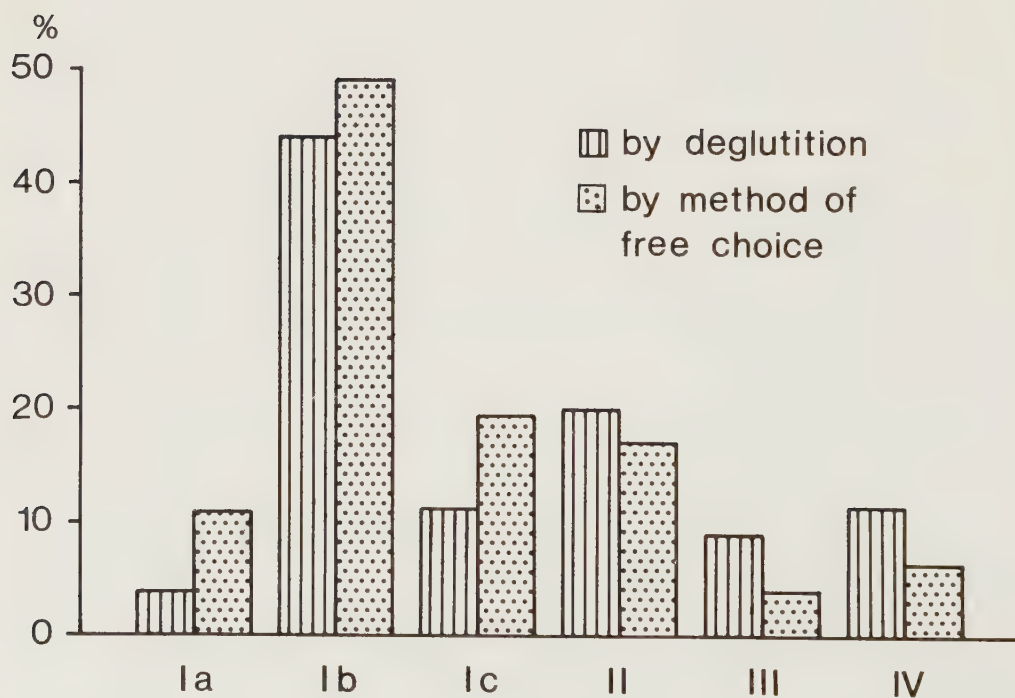


Fig. 3. *Distribution of subjects among tubal function groups by different methods of equilibration.*

Ptm mean
cm H₂O

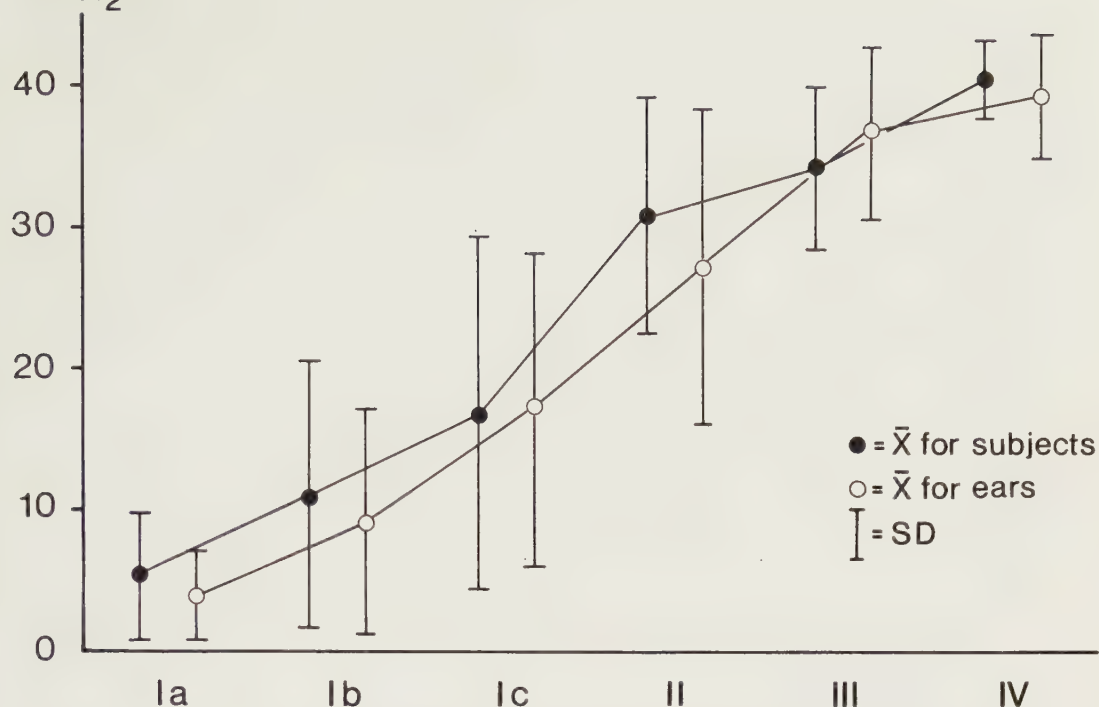


Fig. 4. Mean of Ptm means for different tubal function groups by method of free choice, comparison between ears and subjects.

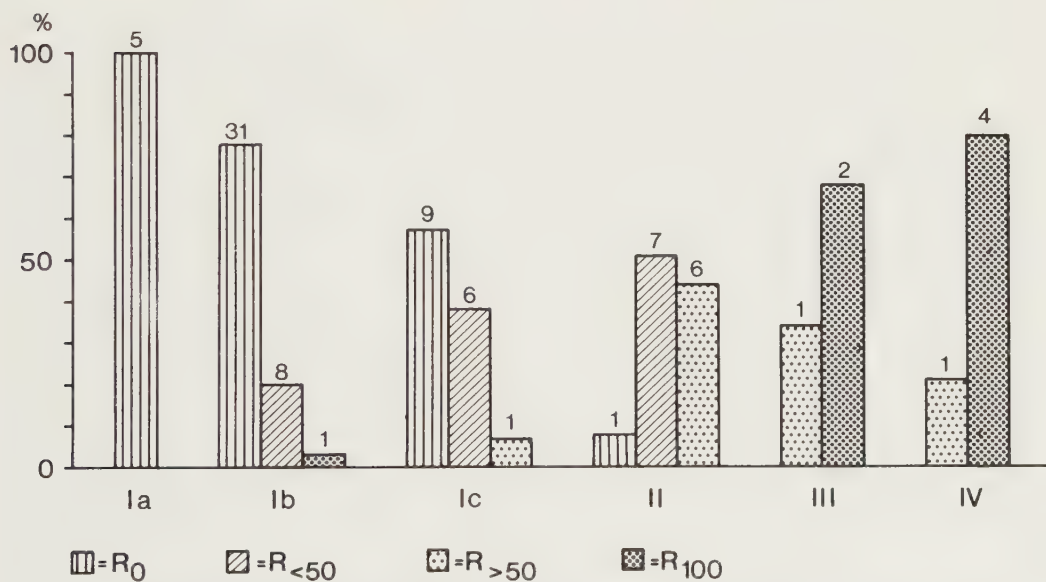


Fig. 5. Frequency distribution of residual pressure groups among tubal function groups by method of free choice in subjects. Figure over histogram denotes number of subjects.

The ability to equilibrate by the method of free choice during simulated descent was calculated in two ways - the mean pressure across the eardrum during descent (P_{tm} mean) and the resulting residual pressure in the middle ear immediately after descent (R). The values found for these two variables were closely correlated with the tubal function, as judged by the ability to equilibrate static over- and underpressures, for single ears as well as for subjects. In Fig. 4, P_{tm} is correlated with tubal function groups, and in Fig. 5 the residual pressure groups are correlated with tubal function groups. Note the dotted histograms (R_{100}) illustrating the seven subjects who could not equilibrate at all.

Fig. 6 shows the correlation between P_{tm} mean and residual pressure groups which is good, but the standard deviation shows overlapping between the groups. The mean pressure opening level was the same in all tubal function groups, for single ears as well as for subjects, except for group Ia - patulous tubes, as can be

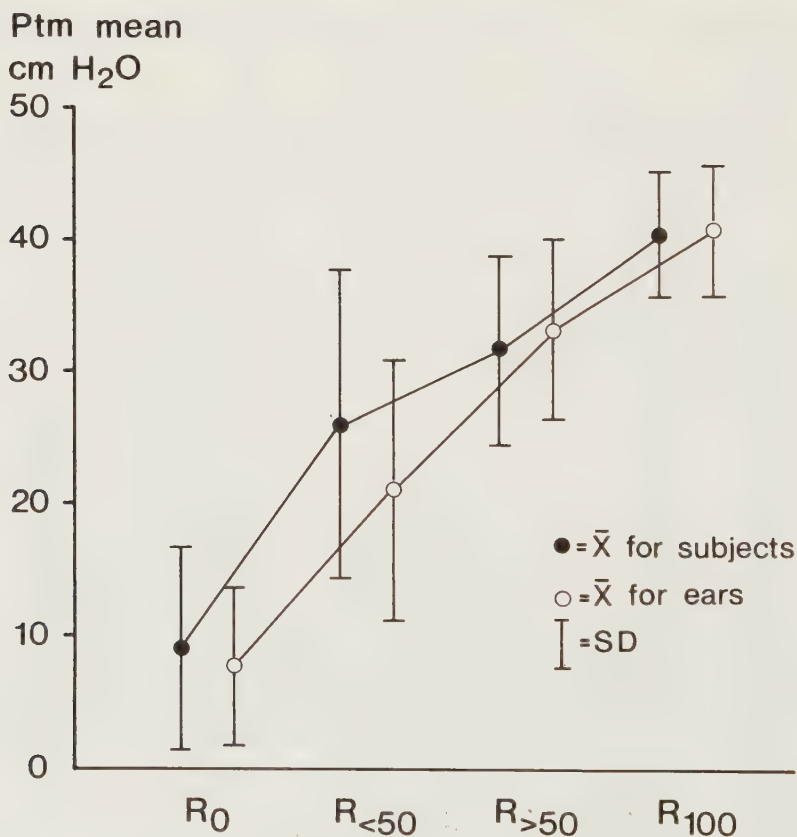


Fig. 6. P_{tm} mean in different residual pressure groups, comparison between ears and subjects.

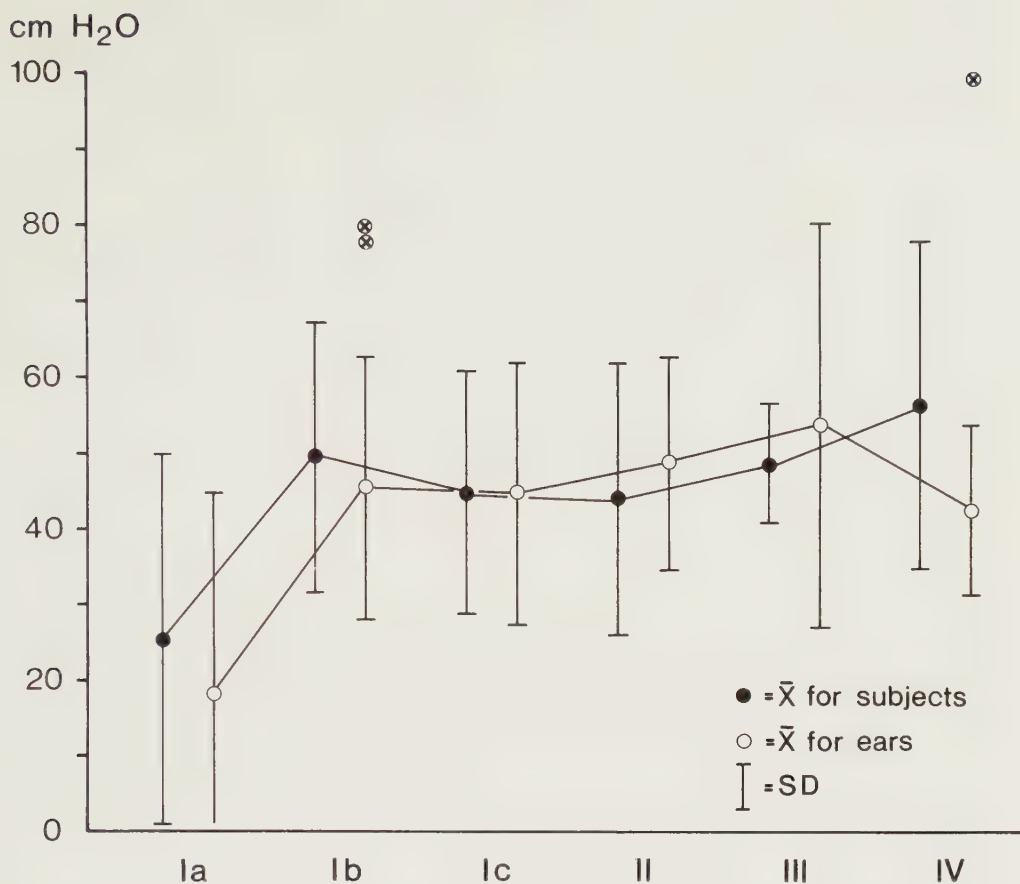


Fig. 7. Mean Pol in different tubal function groups, comparison between ears and subjects.

seen from Fig. 7. Three subjects reported vertigo during the test with pressure opening of the tube during ascent. All three, denoted by (x) in the figure, had asymmetrical equilibration of the middle ear pressure with unilateral pressure opening levels above 60 cm H₂O (5.89 kPa).

The distribution among tubal function groups of the two ears in a subject by the method of free choice is given in Table IV. In 65 % of the subjects the tubal function was equal on both sides. Table V gives the distribution in residual pressure groups for the two ears in each subject; 72 % were symmetrical in this respect.

The correlation coefficient between P_{tm} mean in the two ears of each subject in the entire material was 0.62. The regression line is shown in Fig. 8.

Table IV. *Distribution among tubal function groups by method of free choice for both ears in a subject.*

		left					
		Ia	Ib	Ic	II	III	IV
right	Ia	4	2	1			
	Ib	3	36		1		
	Ic		7	8	4		
	II		2	1	6	1	
	III		2				1
	IV	1		1	1	1	1

DISCUSSION

The results of active equilibration of small static pressure differences across the eardrum by deglutition showed that 20 % of the subjects who had filled the criteria for acceptance as airmen had poor tubal function. The marked improvement in the retest, when the subjects were allowed to equilibrate by the method of free choice, clearly shows that the results of active endeavours to equilibrate differences in pressure across the eardrum can vary with the method used to clear the ears. Our results differ in two respects from those of Elner et al. (7), who found an almost even distribution between groups Ib and Ic and 7 % of the single ears in groups III + IV, compared with our result with almost four times that in group Ib than Ic and 15 % of the single ears in groups III + IV. The ears responsible for this difference of 8 % were all in group II. We can offer no explanation for this difference except the disparity in age distribution between the two materials. In their material, the ages ranged from 17 to 52 (mean 28); in ours, from 17 to 24 (mean 20).

The results of the Valsalva tests were in agreement with those found in earlier investigations. Chunn (3) reported Valsalva's manoeuvre to be positive in all 99 aviation cadets studied. Watson (19) tested 100 experienced pilots without ear problems and found 95 % Valsalva positive. But he also reported that 5 out of 6 pilots with recurrent aerotitis media were Valsalva

Table V. *Distribution of subjects according to residual pressure in both ears.*

	R_0	$R_{\leq 50}$	$R_{>50}$	R_{100}
R_0	46	6	1	
$R_{\leq 50}$	2	2	2	1
right $R_{>50}$	5	10	2	1
R_{100}	1	1	1	2

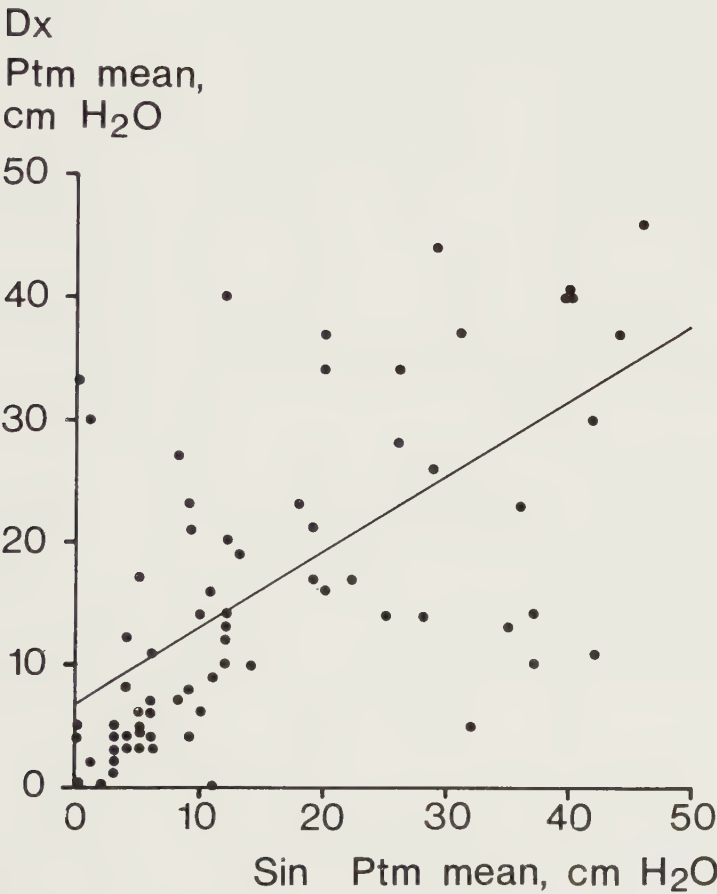


Fig. 8. Correlation for Ptmean between the two ears in a subject. The line shows the calculated linear regression.

negative. In both groups, the results were confirmed by otoscopy. These findings led to a recommendation that the USAF should retain the Valsalva manoeuvre in the examination of candidates for pilot training (AFR 160-1).

Since virtually all our subjects were Valsalva positive, there is no point in comparing with other tests. The Valsalva manoeuvre involves no muscular activity; it only checks tubal patency. A drawback of this manoeuvre is that it can induce convulsive syncope in subjects with low G tolerance (5). Subjects susceptible to alternobaric vertigo may experience this during a Valsalva manoeuvre because of an asymmetric equilibration of the intra-tympanic pressure (8,12,19). This equilibrating technique can, therefore, hardly be recommended for pilots, especially since it requires the use of a hand and possibly at a critical moment. However, it may occasionally be useful if the other means of equilibration should prove ineffective.

A positive Toynbee manoeuvre is widely considered evidence of normal tubal function. Zöllner (20) had 70 % positives in his normal material with very strong correlation to normal tubal function. Elnor et al. (7) had 79 % Toynbee positives, all in tubal function groups I and II. In our material, 80 % of the ears were Toynbee positive, but the negatives were found in all tubal function groups; 31 % of the 89 retested ears and as many as 50 % of the 28 ears that improved when tested with the method of free choice were Toynbee negative. This seems to reflect poor equilibrating ability by deglutition, since they all improved when tested with the method of free choice. Since only five Toynbee manoeuvres were allowed, abortive deglutition is another possible explanation of the failure. As for the Toynbee positives in tubal function groups III and IV, we can find no obvious explanation, but the subjects may perhaps have unconsciously performed additional jaw movements during the manoeuvre, since pilot trainees are often preoccupied with the problem of clearing their ears in different ways. If we should use the results of the Toynbee manoeuvre in our material as a criterion for selection and compare them with the ability to equilibrate dynamic pressure changes, we should not only lose 12 % of the subjects with adequate tubal function, i.e. without residual pressure in the middle ears after descent, because they were Toynbee negative, but also, which may be worse, accept 13 % of the Toynbee positives that could not

equilibrate at all during descent.

Of the ears in the material of Elner et al. (7), 64 % could equilibrate completely during descent, compared with 63 % in our material. In the static test, the corresponding figures were 72 % and 69 % that could equilibrate the negative pressure completely. As can be seen from Fig. 5, 28 % of the subjects in tubal function groups Ib and Ic had various residual pressures in the middle ears after descent. This range of variation indicates that the dynamic pressure test is the more reliable.

The pressure opening level (Pol) does not vary with equilibrating ability, but is important in its connection with alternobaric vertigo. This type of discomfort has been shown to be elicited in the presence of an asymmetric pressure equilibration of the two ears and a unilateral Pol of more than 60 cm H₂O (5.89kPa) in otherwise normal subjects (18). We found six such subjects in our material with a mean pressure difference of 26 cm H₂O (2.55kPa) between the ears. Subjects in tubal function group Ia - patulous tube - did not report any discomfort usually encountered in this condition. The grouping is based on results of static pressure tests, and the fact that we can record an increasing middle ear pressure in some of these ears is probably due to the rate of pressure increase.

We have found no single test or combination of simple tests, such as static pressure equilibration, Valsalva or Toynbee manoeuvres capable of selecting subjects with no residual pressure in the middle ear after descent.

It has often been claimed that tests intended to assess tubal function are not acceptable since they do not reflect the function under normal conditions. However, we think that pilots should be able to equilibrate their ears at any given instant, as they have to do during an actual flight when there is no time to wait and try again. In this respect, the dynamic pressure tests resemble a "normal" situation for airmen.

Since only one ear was tested at a time, the subject had already repeatedly performed the Valsalva and Toynbee manoeuvres, a series of deglutitions, and jaw movements before the second ear was tested. However, there was no difference in results between the ears tested first and those tested second. It was necessary to test both ears in every subject because it is impossible to predict whether the equilibrating ability is equal

on both sides or not. As far as we know, no such study has been performed before. For instance, of the 13 subjects in tubal function group IV judged by swallowing, the ability to clear the ears was equal on both sides in 6. In the remaining 7 subjects, one ear belonged to group IV, the other to some other group(I-III). Four subjects with no residual pressure in one ear had more than 50 % residual pressure in the other.

The wide range of variation in the results of tubal function tests obtained with the microflow method in an otherwise otologically uniform material, indicates that todays criteria for the selection of airmen can be improved. Studies are in progress to find better procedures and criteria.

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EFFECTS OF DIFFERENT BODY POSITIONS ON THE EUSTACHIAN TUBE
FUNCTION IN THE SELECTION OF AIRMEN

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Abstract. The Eustachian tube function of 52 applicants accepted for flight training had earlier been comprehensively tested during simulated flights in a pressure chamber in the sitting position. Despite the fact that all were otologically healthy, the wide range of pressure-equilibrating capacity in the sitting position was even more pronounced when they were retested in recumbency, and in every type of test the pressure-equilibrating capacity was reduced. For instance, 17 % of the recumbent subjects could not equilibrate at all during simulated descent as compared to 8 % in the sitting position; 81 % of the ears were Toynbee positive in the sitting position and only 69 % in recumbency. The advantages of the recumbent compared to the seated test position are discussed.

In the selection of applicants for flight training, a decisive test of the pressure-equilibrating capacity of the Eustachian tube seems important. Today, the applicants are not tested at all in this respect. It is only assumed that the requirements - normal hearing, normal eardrums, and no history of ear disease - imply sufficient tubal equilibrating capacity to avoid ear problems in flight. In an earlier study of 84 applicants accepted for flight training, as many as 20 % could not completely equilibrate static pressure differences in the middle ear and 8 % could not equilibrate at all using deglutitions and jaw movements during simulated descents in the sitting position (7).

It is well known that the pressure-equilibrating capacity is reduced in recumbency, possibly due to tubal mucosal swelling caused by venous and lymphatic stasis (8,14,15,17). This reduction has also been demonstrated during dynamic pressure changes in simulated ascent (9,17) and descent (8,10,11). Ingelstedt et al. (8) stated that slight dysfunction of the tube might more easily be revealed by the recumbent test position.

We decided to test the applicants for flight training in the recumbent position for two reasons: 1) The common cold often causes a reduction of tubal function similar to that of recumbency (15). This is also well known empirically; in fact the common cold is considered one of the most frequent causes of temporary grounding of airmen. The reason for grounding is an increased difficulty to clear the ears in flight which may result in temporarily reduced hearing, pain, and vertigo affecting flight safety. In all incidents reported to the Air Force and Inspection Center during the period 1968-72 an URI was considered a predisposing factor (12); 2) In modern aviation the aircrew is subject to gravitational and accelerative forces in different directions relative to the body position, often corresponding to recumbency. By using the recumbent test position the tube will thus be put to a more strenuous and realistic test. The aim of the present study was to retest 52 of the 84 applicants in the recumbent position in order to provide a further description of their pressure-equilibrating capacity to be used for selection purposes.

MATERIALS AND METHODS

The ability of the Eustachian tube to equilibrate the intra-tympanic pressure during ambient pressure changes was measured with the method devised by Ingelstedt et al. (8) as modified by Elner et al. (3). This method records the volume of air displaced by the movement of the eardrum in response to changes in intra-tympanic and ambient pressures. The recordings were made with the subject in a pressure chamber where ascents and descents could be simulated by pressure changes of ± 50 cm H₂O (± 4.91 kPa) in 25 s at a constant rate of pressure change during 80 % of the time (7).

Fig. 1 shows a recording of the volume of air displaced by movements of the eardrum (V_{tm}), and the pressure in the chamber (P_{ch}) during simulated ascent and descent. The change in chamber pressure from +50 to -50 cm H₂O (+4.91 to -4.91 kPa), as in ascent, causes an increasing overpressure in the middle ear that moves the drum outwards until the tube is forced open passively. The pressure needed for this is derived from the P_{ch}-curve and is called pressure opening level (P_{ol}). After the drum has been brought back to its neutral position by repeated deglutitions (arrows A), the pressure change is reversed simulating descent. During descent, the subject is told to equilibrate as best he can using deglutitions and jaw movements, i.e. the method of free choice (arrows B). From this recording we can calculate the mean deviation of the drum from its neutral position (V_{tm} mean) by planimetry, and the corresponding mean pressure across the eardrum, P_{tm} mean (Δ P_{ch} at V_{tm} mean). The residual pressure in the middle ear immediately after descent (R) is calculated as the percentage of the total pressure change during descent. Both P_{tm} mean and R are then used as measures of the pressure-equilibrating capacity of the Eustachian tube.

Performance: The purpose of the tests was explained and instructions and demonstrations of Valsalva's and Toynbee's manoeuvres were given. The subject was placed in a convertible chair. The tests were made first in the sitting and then in the dorsal recumbent position without alteration of the recording equipment. Active equilibration of static over- and underpressures of 10 cm H₂O (0.98 kPa) by the method of free choice was only performed

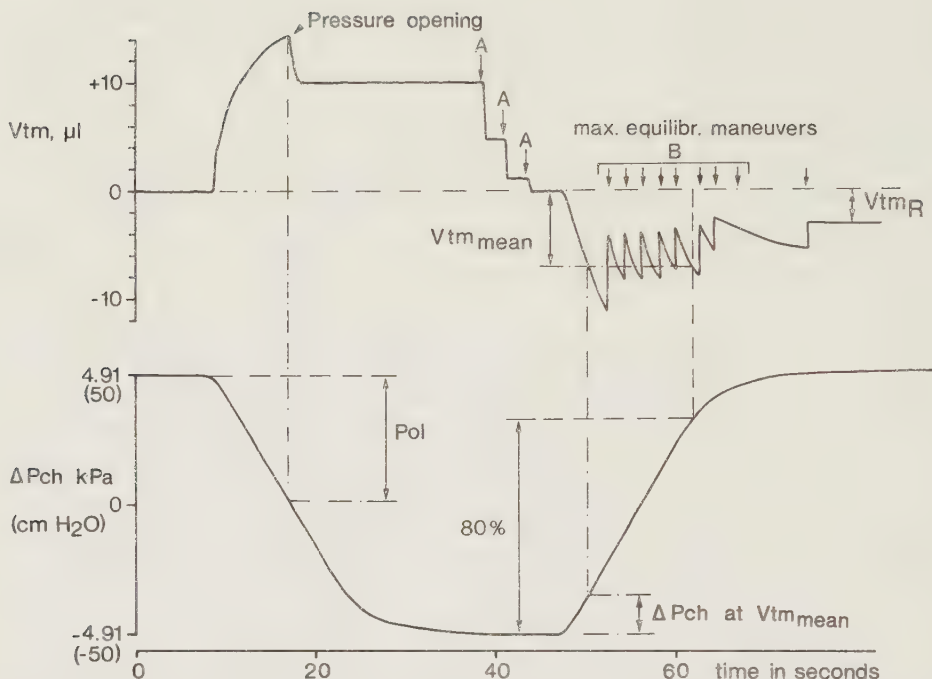


Fig. 1. Example of recording of eardrum displacement (V_{tm} in μl) and chamber pressure (P_{ch} in $cm\ H_2O$ or kPa). Pol indicates pressure opening level and V_{tmR} indicates eardrum displacement at residual pressure R .

in the sitting position to allow the distribution of ears and subjects into tubal function groups according to Elner et al. (4), where Group I equilibrates both over- and underpressures completely, Group II equilibrates with small residual pressures, Group III equilibrates overpressures like Group II but not underpressures, and finally Group IV cannot equilibrate at all. Recordings were made from one ear at a time and the tests were made in the following order:

1. Valsalva's and Toynbee's manoeuvres: Displacement of air by the movement of the eardrum when the subject performed the manoeuvres was recorded as positive. Five tries for each manoeuvre were allowed.

2. Active equilibration of dynamic pressure differences across the eardrum during simulated descent. The resulting $P_{tm\ mean}$ was calculated as described above. The residual pressures are shown

in four groups:

R_0 = No residual pressure in the middle ear (at most 4 %)

$R_{\leq 50}$ = 5-50 % residual pressure.

$R_{>50}$ = 51-95 % residual pressure.

R_{100} = 96-100 % residual pressure.

3. The pressure opening level (Pol) of the tube was determined during simulated ascent. The subject was not allowed to equilibrate during this test.

RESULTS

We tested 52 subjects in both body positions at the same session. The results are presented for both single ears and subjects. If the result of a test was poorer in one ear than in the other, the poorer result was taken as representative of the subject. Valsalva's manoeuvre was positive in all but two ears in two subjects in the sitting position. These two remained negative, and only 1 ear in a third subject changed to negative when the test was repeated in the recumbent position.

Toynbee's manoeuvre was positive in 81 % of the ears in the sitting and in 69 % in the recumbent position. The corresponding figures for subjects were 71 % and 58 %, respectively. The distribution in tubal function groups according to Elner et al. (4) for single ears is given in Table I.

Table I. *Results of Toynbee's manoeuvre in different tubal function groups, by the method of free choice, in the sitting and recumbent position in single ears.*

	Sitting			Recumbent		
	Pos	Neg	Pos(%)	Pos	Neg	Pos(%)
I	71	11	86	62	20	76
II	11	7	61	8	10	44
III	2	1	67	2	1	67
IV	-	1	-	-	1	-

Table II. *Distribution of single ears in residual pressure groups in the sitting and recumbent positions.*

	Sitting		Recumbent	
	Nb	(%)	Nb	(%)
R_0	65	(62)	45	(43)
$R_{\leq 50}$	28	(27)	24	(23)
$R_{>50}$	8	(8)	24	(23)
R_{100}	3	(3)	11	(11)

Table III. *Distribution of subjects in residual pressure groups in the sitting and recumbent positions.*

	Sitting		Recumbent	
	Nb	(%)	Nb	(%)
R_0	28	(54)	16	(31)
$R_{\leq 50}$	15	(29)	12	(23)
$R_{>50}$	6	(11)	15	(29)
R_{100}	3	(6)	9	(17)

The capacity to equilibrate by method of free choice during descent was measured as P_{tm} mean and R. The mean of P_{tm} means in all 104 ears was 14.2 cm H₂O (S.D. $\pm$ 12.8) sitting and 19.1 cm H₂O (S.D. $\pm$ 14.4) recumbent. The corresponding figures for subjects were 18.1 cm H₂O (S.D. $\pm$ 14.0) and 23.5 cm H₂O (S.D. $\pm$ 15). The differences are highly significant ($p < 0.001$, Student's t-test) between the two body positions for both single ears and subjects. Since subjects are represented by the ear with the poorer result, we find higher values for P_{tm} mean in subjects. The distribution in tubal function groups for single ears is shown in Fig. 2. The residual pressures (R) in both body positions for single ears are shown in Table II and for subjects in Table III.

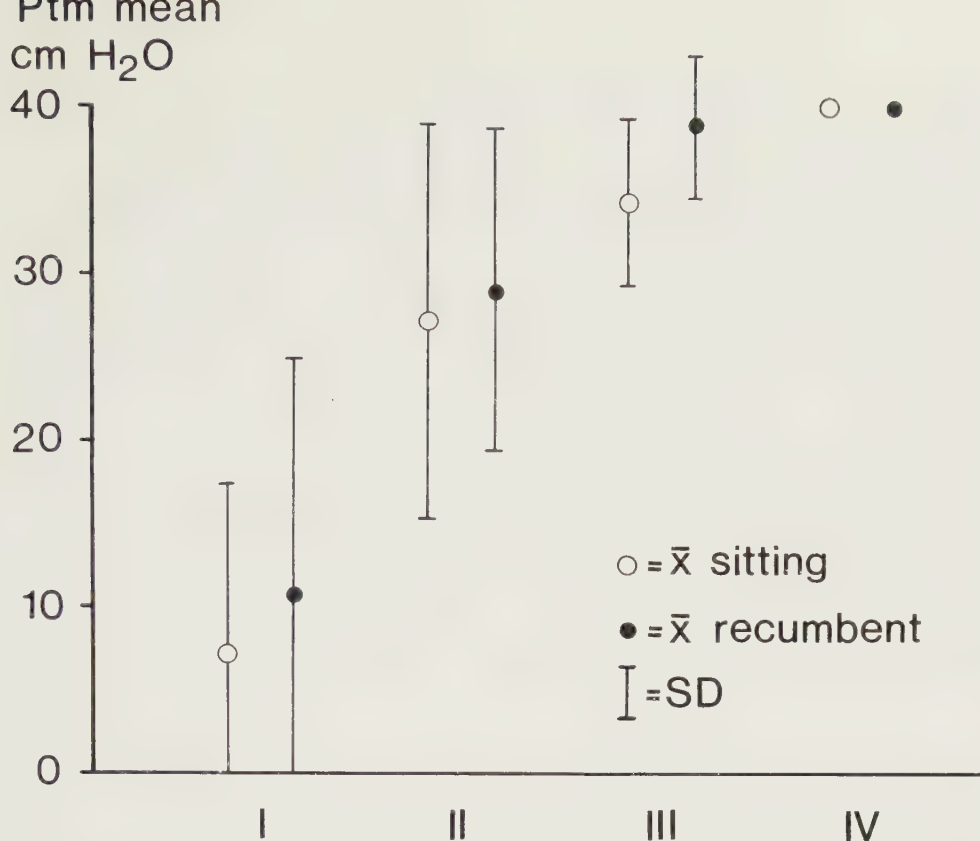


Fig. 2. Mean of Ptm means for different tubal function groups in the seated and recumbent positions in single ears.

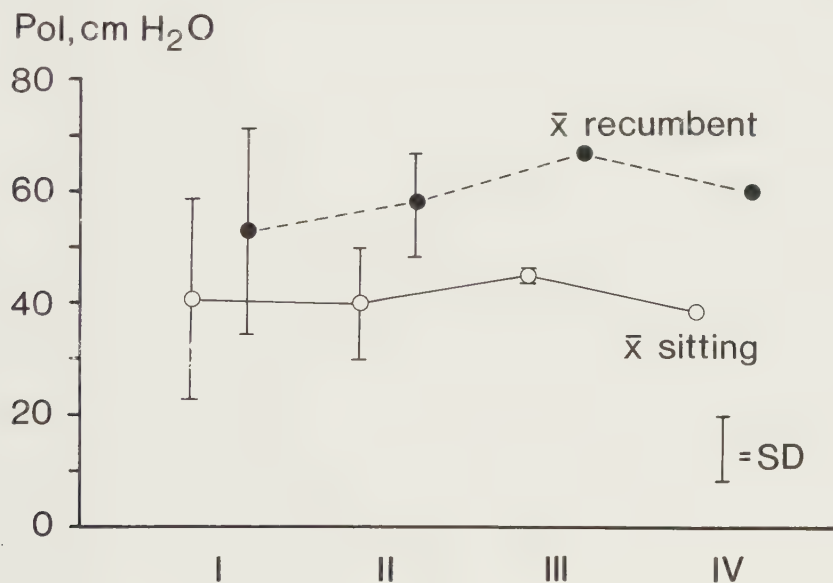
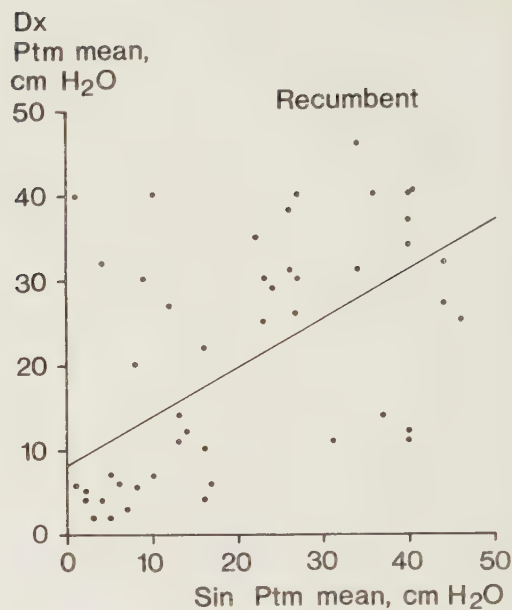
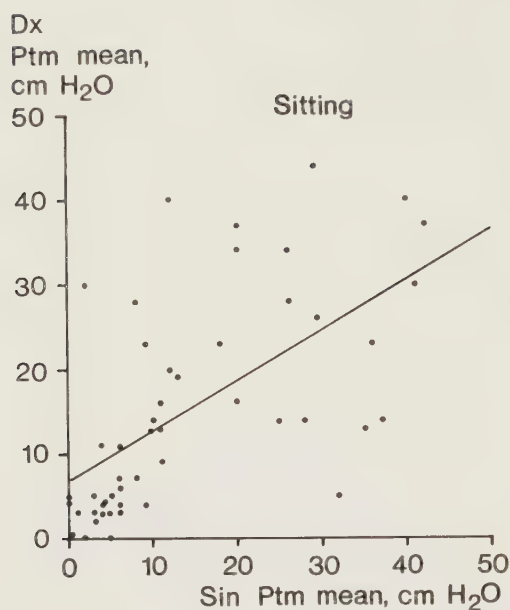


Fig. 3. Pol in different tubal function groups by method of free choice. A comparison between the seated and recumbent positions in single ears.



Figs 4 and 5. Correlation of Ptm mean for the two ears in every subject in the seated and the recumbent position.

Table IV. Distribution in residual pressure groups of the two ears in every subject in the sitting and recumbent positions.

		Sin							
		Sitting				Recumbent			
		R ₀	R _{<50}	R _{>50}	R ₁₀₀	R ₀	R _{<50}	R _{>50}	R ₁₀₀
Dx	R ₀	28	3	1	1	16	3	—	2
	R _{<50}	3	9	2	—	6	3	3	2
	R _{>50}	1	1	1	1	1	4	7	—
	R ₁₀₀	—	1	—	—	1	—	2	2

The mean of the pressure opening levels (Pol mean) in single ears during ascent in the sitting position was 40.4 cm H₂O (S.D. $\pm$ 17.6) and 54.3 cm H₂O (S.D. $\pm$ 17.9) in the recumbent position. The corresponding figures for subjects were 46.2 cm H₂O (S.D. $\pm$ 16.5) and 59.2 cm H₂O (S.D. $\pm$ 16.9). This difference between the two body positions is also highly significant ($p < 0.001$, Student's t-test) for both single ears and subjects. The distribution in tubal function groups for single ears in both positions is given in Fig. 3.

The correlation coefficient for P_{tm} mean in the two ears in every subject was 0.59 in both the sitting and the recumbent position. The regression lines are given in Fig. 4 and 5. The distribution in residual pressure groups for the two ears in every subject is given in Table IV; for this, 73 % of the subjects were symmetrical in the sitting and 54 % in the recumbent position.

DISCUSSION

The results of the Valsalva manoeuvre in the two body positions were almost the same, as only one ear changed to be negative in the recumbent position. The increase in the hydrostatic venous pressure in the tubal mucosa, in the recumbent position, seems not to be large enough to resist the pressure increase in the nasopharynx during the Valsalva manoeuvre except in this single case. The two subjects who were Valsalva negative in the sitting position could equilibrate completely during descent by method of free choice in the sitting position, but had residual pressures of 100 % and less than 50 %, respectively, in recumbency. The third subject could equilibrate completely during descent in both body positions. All three belonged to tubal function group I. These results further support the opinion that a positive Valsalva manoeuvre provides no useful information beyond that of tubal patency. We cannot recommend the Valsalva manoeuvre as a routine because of its well-known drawbacks; it may induce convulsive syncope (2), alternobaric vertigo (5,13,18) and the subject needs a free hand and access to the nose. The muscular opening function in Toynbee's manoeuvre seems to be reduced in recumbency due to mucosal swelling of the tube. This may explain the reduction of Toynbee positives from 81 % to 69 % in recumbency. These results are in good agreement with the 72 % Toynbee positives in Thomsen's

normal material (16), also tested in the recumbent position. While 53 % of the Toynbee positives could not equilibrate completely while recumbent, 16 % of the Toynbee negatives could equilibrate completely in the same position. This means that, if we should use a positive Toynbee's manoeuvre as a selection criterion, we would not only accept subjects with residual pressures in the middle ears after descent but also reject those with adequate tubal function because they were Toynbee negative.

The capacity to equilibrate by method of free choice during simulated descent was also reduced in recumbency, measured both as P_{tm} mean and R. Because of differences in equilibrating technic, P_{tm} mean varies considerably in group R₀. Frequent and efficient equilibrations give a low P_{tm} mean value, and a few but very substantial equilibrations give a higher value but still complete equilibration. Therefore, P_{tm} mean should be regarded as a measure of how equilibration is achieved, and R as the more reliable measure of the wanted qualification. Another factor separating P_{tm} mean and R is time, P_{tm} mean is calculated on 80 % of the time of pressure change, when the velocity is constant, but R is calculated on 100 % of the time. The difference is about 8 s, and during this time the P_{tm} mean might have changed further. Objections might be made to the way in which R is determined, because if a subject had had one more successful equilibration before the end of the pressure change, a smaller R would have resulted. Here, the strong correlation between P_{tm} mean and R_{>50} or R₁₀₀ supports our belief that R is a reliable measure, because it is very unlikely that an attempt to equilibrate by method of free choice would be successful only in the end of descent when the growing underpressure in the middle ear makes it harder or even impossible (1,6). The Pol was significantly increased for the whole material in the recumbent position in agreement with earlier findings of Ingelstedt et al. (8) and Tjernström (17). The pressure increase did not result in more cases of alternobaric vertigo, which accords with Tjernström's findings. The asymmetry of R between the two ears in the subjects was more pronounced in recumbency, but this seems only to be a consequence of the poorer results.

Thus, in all types of tests used in this study, we find reduced equilibrating capacity in the recumbent compared to the seated position. The positional effect seems to be comparable to the

effect of a common cold on the equilibrating capacity (15).

This reduction is similar to the effect of a common cold on the Eustachian tube. Flying personnel are, therefore, requested not to fly when they have a cold, but it is well known that many fly just the same. It is also possible that colds mild enough to be neglected reduce the tubal function in a decisive way. The recumbent test position offers an opportunity to find out what will happen to the equilibrating capacity during a cold. Those who can equilibrate completely in recumbency certainly should stand a better chance to fly without ear trouble even though they have a cold, thus demonstrating a reserve capacity. In this study, only 30 % equilibrated completely in recumbency. If this capacity had been a requirement for flight trainees, it would very likely reduce the number of interrupted training sessions, raise the mission capacity, and increase the fitness for use.

A suitable level of tubal function in airmen is, of course, a question of supply and demand, but a correlation between test results and the actual results of flight training is necessary. Such a correlation is not easily evaluated. The rates and amounts of pressure changes during actual flight will be much higher than in the tests, where injuries to the subject must be avoided. It is also difficult to exclude other causes of failure. In the following study, a retest of these subjects will be made after the primary flight training in order to evaluate a possible change - a training factor - in the equilibrating capacity of the Eustachian tube.

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COMPARISON OF EUSTACHIAN TUBE FUNCTION MEASURED BY THE
MICROFLOW METHOD AND A NEW QUANTITATIVE IMPEDANCE METHOD

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Abstract. The Eustachian tube function in 25 applicants for flight training was tested during simulated flights using the integrating microflow method with a stationary pressure chamber and a new quantitative impedance method in combination with a new mobile pressure chamber alternately. All ears were tested by both methods. The results in the various tests did not differ significantly between methods. The reliability of the measurements was good and almost equal in both methods. Several practical advantages with the new impedance method in combination with the mobile pressure chamber make it preferable.

INTRODUCTION

The need for a quantitative method to evaluate the Eustachian tube function continuously has been stressed earlier (4,8). The integrating microflow method seems to meet this requirement and an account of the Eustachian tube function in applicants accepted for flight training tested with this method has been provided (4,5,6). Our experiences of this method are very good. Since 1967 several investigations of the Eustachian tube function and middle ear mechanics in normal ears have been made (3,8). However, recordings and calculations are very laborious and time-consuming, and gradually the need for a simpler method to satisfy the demands in clinical routine work in this field has become evident.

For this purpose a simplified method based on the principle of the conventional acoustic impedance bridge has been devised (9). The method records quantitatively and continuously changes in compliance of the eardrum in relation to maximum compliance in response to changes in the ambient pressure as in ascent and descent. The aim of this study was to test different variables of the tubal function in applicants accepted for flight training using the microflow method and the new impedance method in the same subjects on the same occasion and also to compare results by the two methods in single ears in order to find out if the new method is a useful replacement in this type of investigation.

MATERIAL AND METHODS

The material consisted of 25 applicants accepted for flight training. Microotoscopic examination including Siegle's test and audiography (within 20 dB ISO, 1964) had revealed nothing remarkable and no one had a history or signs of a recent URI. Using a stationary pressure chamber and the method described by Ingelstedt et al. (8) and Elnor et al. (2) the pressure equilibrating capacity of the Eustachian tube was studied. The method records the volume of air displaced by movements of the eardrum in response to changes in the intratympanic and ambient pressures, simulating ascent and descent, corresponding to ± 50 cm H₂O in 25 s. The neutral position of the eardrum is defined as the position when there is no pressure difference across it. A diagram of the recording equipment together with a recording example is given in Fig. 1. A polyethylene catheter was fitted

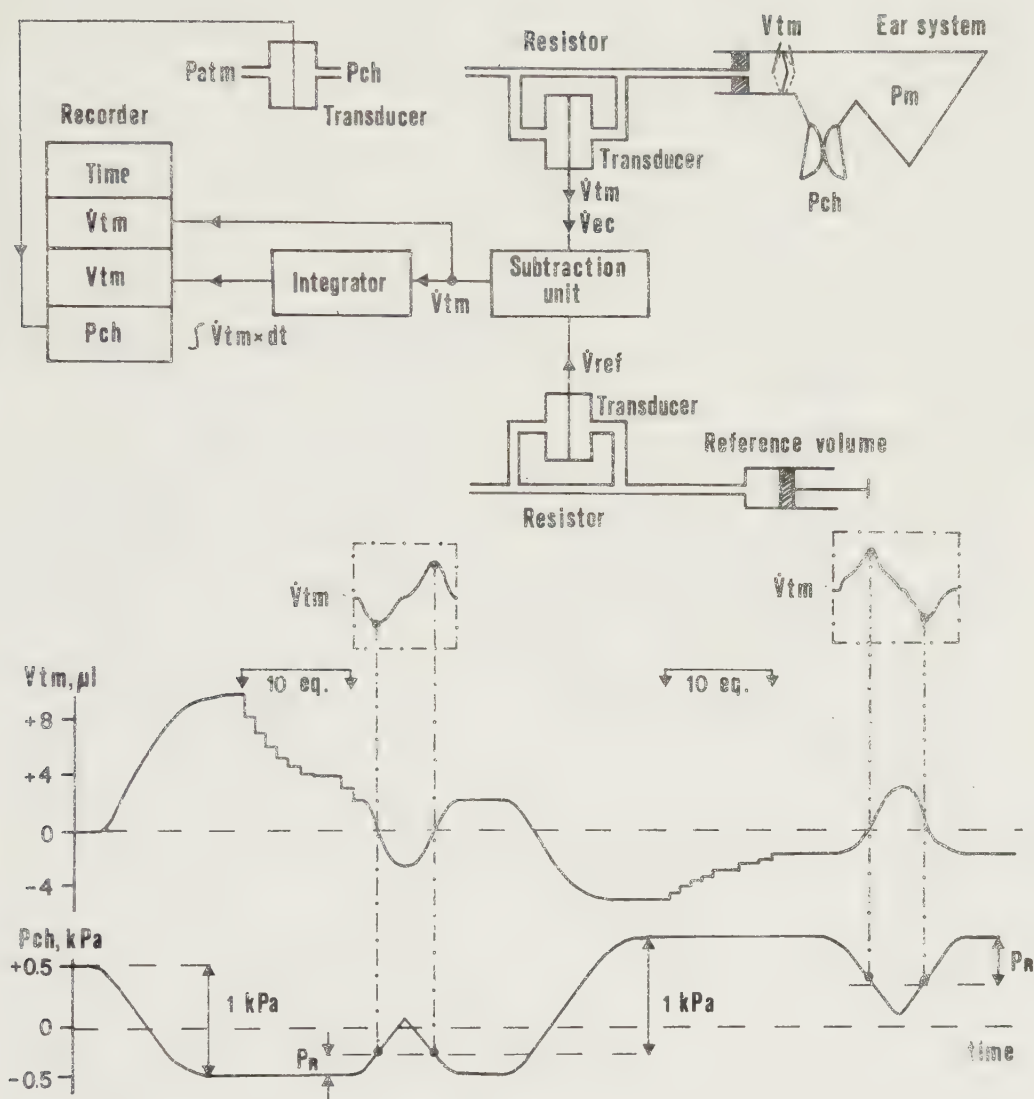


Fig. 1. Method I: Equipment used for recording of eardrum displacement (V_{tm}) on change of ambient pressure (P_{ch}). Recording example: Residual pressure (P_R) after equilibration of -1 and +1 kPa in the lower curve. The neutral position of the eardrum is identified by maximum airflow ($\dot{V}_{tm}$). 1 kPa $\approx$ 10 cm H₂O. For details, see text.

airtight in the bony part of the ear canal by a physician, preferably in an otomicroscope. The other end of the catheter is in open contact with the pressure chamber via a flowmeter. This arrangement made it possible to record the airflow ($\dot{V}_{tm}$) caused by eardrum movements in response to changes in the intratympanic pressure (P_m). However, when the ambient pressure (P_{ch}) was changed, the airflow was influenced also of compression and expansion of air in the system ($\dot{V}_{ec}$). The latter component was corrected for by introduction of a reference system ($\dot{V}_{ref}$) operating an identical flowmeter. In the properly balanced system, the signals from $\dot{V}_{ec}$ and $\dot{V}_{ref}$ cancelled out each other and the resulting signal $\dot{V}_{tm}$ was integrated with respect to time to allow the recording of the isolated volume of air displaced by movements of the eardrum. This arrangement practically limits the method to recording of one ear at a time. This method will be referred to as method I. A more detailed description of method I is given by Groth et al. (4).

The quantitative impedance method is used with a small mobile pressure chamber which yields the same rate and amount of pressure change as method I. The impedance method records continuously changes in the eardrum compliance in relation to maximum compliance during changes in the intratympanic and ambient pressures. The neutral position of the eardrum is defined as the position that provides maximum compliance. In contrast to method I, the ear cuffs may be inserted easily by the technician or even by the test subject. The method allows simultaneous measurement in both ears and will be referred to as method II. A block diagram of the recording apparatus and a recording example is shown in Fig. 2.

PERFORMANCE

In every other subject the test program was run first by method I and then by method II, and in every other subject vice versa to eliminate any influence of the order of the methods used. Both ears were tested in every subject, one at a time by method I and both ears simultaneously by method II. The subject was sitting comfortably in both pressure chambers. Two technicians were used, one for each method. Instructions to the subject during the tests were identical for both methods. All subjects were

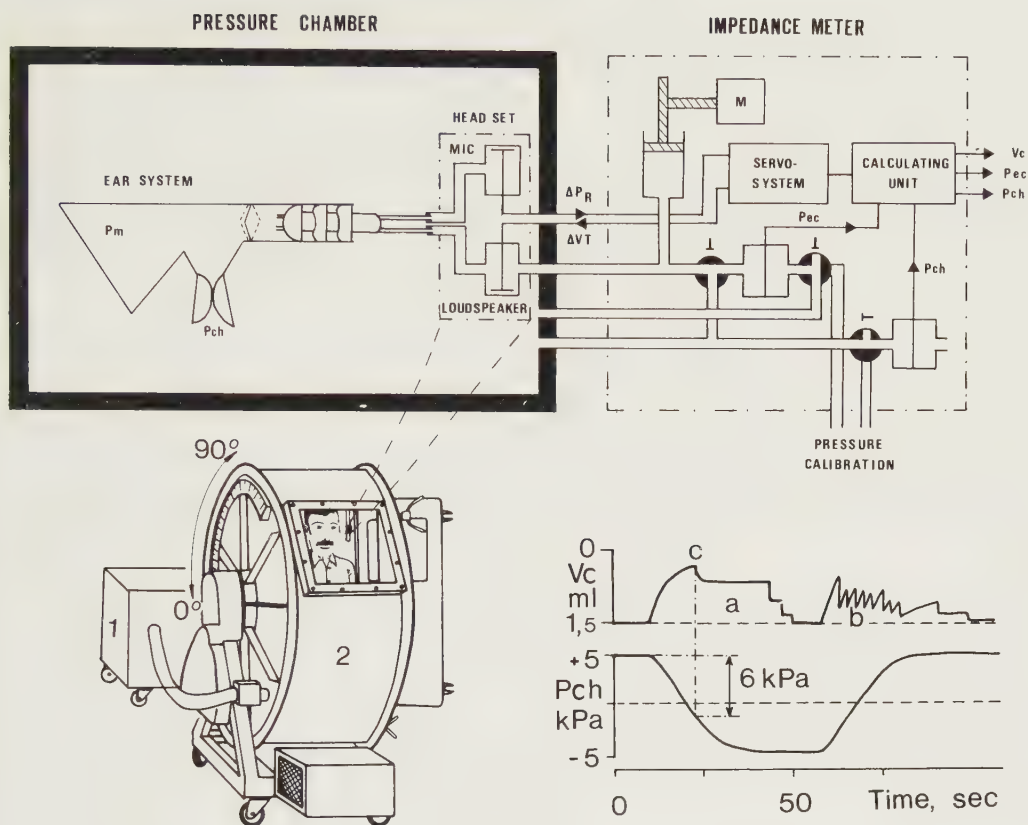
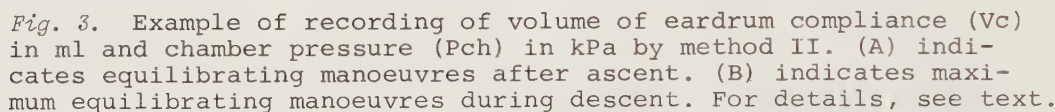


Fig. 2. Method II: Pressure chamber (1,2), servoregulated impedance meter including calculating unit used for recording of changes in eardrum compliance on ambient pressure changes. Recording example: Volume recording of eardrum compliance (V_c) in upper curve, on change of chamber pressure (P_{ch}) in lower curve, during ascent (a), descent (b) and pressure opening level at 6 kPa (c). Maximum compliance level recorded at 1.5 ml. A more detailed description of the equipment in method II is provided by Ivarsson et al. (9).



1. Pressure opening level (Pol). During ascent, the increasing overpressure in the middle ear eventually forces the tube open and air escapes through the tube. The pressure needed to force the tube open is read from the Pch curve in the same way for both methods. The subject is not allowed to equilibrate during this test. The test was repeated 3 times. Fig. 3 shows the recording by method II. The procedure by method I is identical.

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repeated 3 times.

3. The residual pressure in the middle ear immediately after descent (P_R) causes a displacement of the drum from its neutral position and the corresponding pressure change to regain the neutral position is calculated and P_R is provided in % of the total pressure change, see Fig. 3. The test was repeated 3 times.

4. The residual pressure in the middle ear after equilibration of +10 and -10 cm H₂O static pressure level in the middle ears by 10 deglutitions in 3 minutes (P_R) is calculated by the same procedure as above. The test was not repeated.

In order to calculate the residual pressures after equilibration of either static or dynamic pressure changes, the neutral position of the eardrum is determined; for method I as the moment of maximum airflow ($\dot{V}_{tm}$) (Fig. 1) and for method II as the moment of maximum compliance (Fig. 4). These positions are determined by changing the chamber pressure.

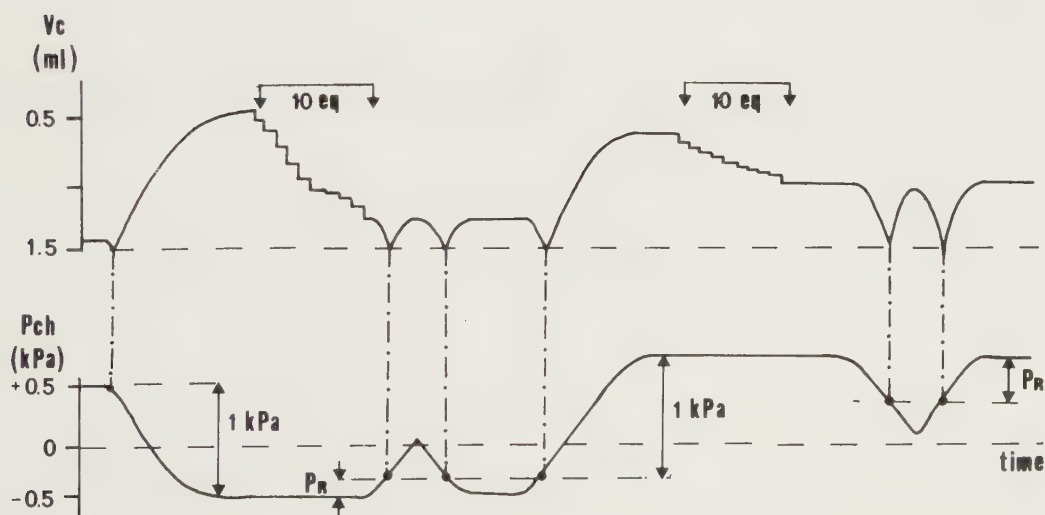


Fig. 4. Recording example of determination of residual pressures after equilibration of -1 and +1 kPa. 1 kPa $\approx$ 10 cm H₂O. 10 equilibrating manoeuvres were allowed (10 eq.).

RESULTS

Comparisons of the results in single ears recorded by the two methods were made using Student's t-test for all variables. In order to make a meaningful comparison between methods, the reliability, i.e. the variation in the recorded results caused by variations in the recording apparatus, the test subject and the technician, must be known. The reliability in results is presented as standard deviation for each variable and was calculated as follows. The pooled estimate of the variance was computed by first obtaining the variance of the 3 measurements in each ear. Then the square root for the mean variance of all ears was calculated.

1. *The pressure opening level* during simulated ascent (Pol) was recorded 3 times. In the first 2 measurements Pol was significantly higher recorded by method II than by method I. In the third recording there was no significant difference in results between the methods. Results are shown in Table I. The reliability of Pol by method I was 3.41 and by method II 2.92 cm H₂O.

2. *The mean pressure difference across the eardrum* recorded during simulated descent (Ptm mean) is presented in Table II. The reliability of Ptm mean by method I was 3.03 and by method II 3.67 cm H₂O.

3. *The residual pressure in the middle ear* recorded immediately after descent is shown in Table III. The reliability of P_R by method I was 7.98 and by method II 10.21 %.

4. *The static pressure equilibration* of ± 10 cm H₂O is shown in Table IV. There is no difference in the results between methods for overpressures, but a doubtfully significant difference for underpressures.

Variation in the number of ears accounted for in different recordings is due to difficulties in obtaining accurate recordings from ears with tuba aperta, leaking ear cuffs or artifacts from deglutitions. Failure by one method automatically makes the recordings by the other method in that ear useless since all comparisons are made from results in single ears.

Table I. Comparison of the pressure opening level (Pol) in cm H₂O by method I and II presented as mean values, SD and results of Student's t-test.

Recording	No	Method I	Method II	P
1	36	32.86 $\pm$ 10.07	36.64 $\pm$ 10.72	< 0.01
2	35	30.74 $\pm$ 9.88	33.40 $\pm$ 10.44	< 0.05
3	33	31.27 $\pm$ 11.35	33.24 $\pm$ 10.61	n.s.
all	104	31.64 $\pm$ 10.37	34.47 $\pm$ 10.61	< 0.001

Table II. Comparison of the mean pressure difference across the eardrum during descent (P_{tm} mean) in cm H₂O by method I and II presented as mean values, SD and results of Student's t-test.

Recording	No	Method I	Method II	P
1	47	12.75 $\pm$ 11.19	11.57 $\pm$ 10.80	n.s.
2	45	14.11 $\pm$ 11.61	11.33 $\pm$ 10.98	< 0.05
3	44	14.30 $\pm$ 11.61	12.60 $\pm$ 11.73	n.s.
all	133	13.59 $\pm$ 11.40	11.71 $\pm$ 11.08	< 0.05

Table III. Comparison of the mean residual pressure in the middle ear after descent (P_R) in % of the total pressure change by method I and II presented as mean values, SD and results of Student's t-test.

Recording	No	Method I	Method II	P
1	47	15.74 $\pm$ 27.55	20.49 $\pm$ 29.07	n.s.
2	45	17.76 $\pm$ 29.49	17.96 $\pm$ 27.16	n.s.
3	42	19.45 $\pm$ 29.46	20.31 $\pm$ 29.60	n.s.
all	134	17.58 $\pm$ 28.68	19.59 $\pm$ 28.44	n.s.

Table IV. Comparison of the residual pressure in the middle ear after equilibration of static over- and underpressures of $\pm$ 10 cm H₂O by method I and II presented as mean values, SD and results of Student's t-test.

Static pressure level	No	Method I	Method II	P
+ 10 cm H ₂ O	44	0.71 $\pm$ 1.49	0.71 $\pm$ 1.37	n.s.
- 10 cm H ₂ O	44	1.93 $\pm$ 2.53	1.15 $\pm$ 2.58	< 0.05

DISCUSSION

In the repeated recordings of Pol by method I the results are reproducible as compared to results by method II, where a lowering of Pol between recordings is evident. Cantekin et al. (1) found that the first recorded value of Pol is higher than the following, and stated that this lowering was presumably caused by the fact that the first pressure opening changed the surface tension and other qualities of the mucus in the tubal lumen facilitating the next tubal opening. This difference in the results of Pol between the methods seems to be related to the difference in procedure before the actual recordings. In method I the tube was repeatedly forced open by Valsalva manoeuvres necessary to balance the 2 flowmeter systems of the recording equipment before the recordings of Pol (2). In method II this procedure is not needed and recordings of Pol were made without preceding Valsalva manoeuvres, which seem to condition the tube to open more easily in the same way as pressure openings. After the 2 first pressure openings by method II Pol is lowered so that the difference in the results between methods is not significant in the third recording. This lowering of Pol in the first recordings has also been observed in a study where 10 repeated recordings of Pol were made (7).

As to the other variables there were no differences in procedure before testing and the statistical evaluation could not show any significant differences in results between methods. The differences were all well within the range of the standard deviations representing the reliability in measurements for each variable and method.

Differences in reliability between the methods were not more than 0.49 cm H₂O for Pol, 0.64 cm H₂O for P_{tm} mean and 2.32 % for P_R, and in this respect the 2 methods may be regarded as equal. Therefore even results in earlier studies with the microflow method may be used for comparison with further investigations using the impedance method. However, for practical purposes method II combined with the mobile pressure chamber should be preferred. The stationary chamber and the microflow method requires a physician and an otomicroscope for ear cuff insertion, the volume balance procedure is complicated and time-consuming (2), and prevents simultaneous measurement of both ears in a subject. The impedance method can be handled by the technician alone. It

is time-saving, less than half the time that is needed by the microflow method, and in that time both ears are measured as compared to only one ear in the microflow method. These qualities make the impedance method suited not only for a comprehensive selection program, but also in every-day care as an aid to the physician assessing the fitness of a member of an air crew to resume flight duty after an URI. It is probably common that air crews are grounded longer than necessary or sent back to flight duty too soon when having a cold. The reason for this is that the physician lacks a method to assess their capacity to clear the ears in flight with certainty.

CONCLUSION

The new impedance method in combination with the mobile pressure chamber seems to have overcome the drawbacks of the microflow method without losing in precision and offers a more practical means to assess the equilibrating capacity of the Eustachian tube in air crews.

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EFFECT OF FLIGHT ON THE EUSTACHIAN TUBE FUNCTION AND THE TYMPANIC MEMBRANE SYSTEM - A FOLLOW-UP STUDY

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Abstract. The Eustachian tube function in 32 aviation trainees was comprehensively tested in simulated flights in a pressure chamber on 3 occasions during their training. Their mean flight experience between tests comprised 150 hours in jet training planes and 260 hours in jet fighters. Their capacity to clear the ears in descent did not improve convincingly between tests, but the pressure opening level in ascent was significantly lowered. The elasticity of the eardrum system was significantly increased. The results suggest that the first test, before the flight training, is reliable for selection purposes. Reasons for difficulties in finding good agreement between test results and results of actual flight training are discussed.

INTRODUCTION

The pressure equilibrating capacity of the Eustachian tube in otologically healthy subjects may be considered stable. Only small variations in both active (6,11) and passive (14) equilibrating capacity are found at repeated tests at intervals of up to several months. Results in different normal materials are also in very good agreement (6,8,17). In 1971 Elner et al. (7) showed a relation between reduced tubal function and increased mobility of the eardrum system, i.e. the drum, ossicles, ligaments and muscles of the middle ear, presumably caused by a more or less constant pressure gradient across the eardrum. Ivarsson et al. (15) reported that experienced divers with a good tubal function had a greater mobility of the eardrum system as compared to healthy non-divers. Thus, increased mobility of the eardrum system seems to be the result of pressure loads across the drum either because of reduced tubal function or considerable changes in the ambient pressure.

Since airmen as well as divers also experience such pressure loads caused by ambient pressure changes it was considered of interest to find out if flight training leads to similar changes, not only in the eardrum system, but also in the Eustachian tube function. Such changes might improve the capacity to clear the ears in flight and constitute a possible training factor. There is no consensus of opinion among airmen that the capacity to clear the ears in flight improves with time (3), but it is a common observation that experienced aircrews suffer less from ear trouble in flight than students (2). Whether this difference is caused by training or is a result of simple selection is not known since comparative quantitative tests of the pressure equilibrating capacity of the Eustachian tube before and after flight training have not been reported earlier.

The aim of the present study was to evaluate the influence of flight training on 1) the elasticity of the ear drum system and 2) the equilibrating capacity of the Eustachian tube and its significance for the selection procedure. A comparison of results of different tubal function tests in accepted applicants performed on 3 different occasions during the flight training was made. Test 1 was performed before the primary flight training. The time for the second test, 1 year later and after the primary

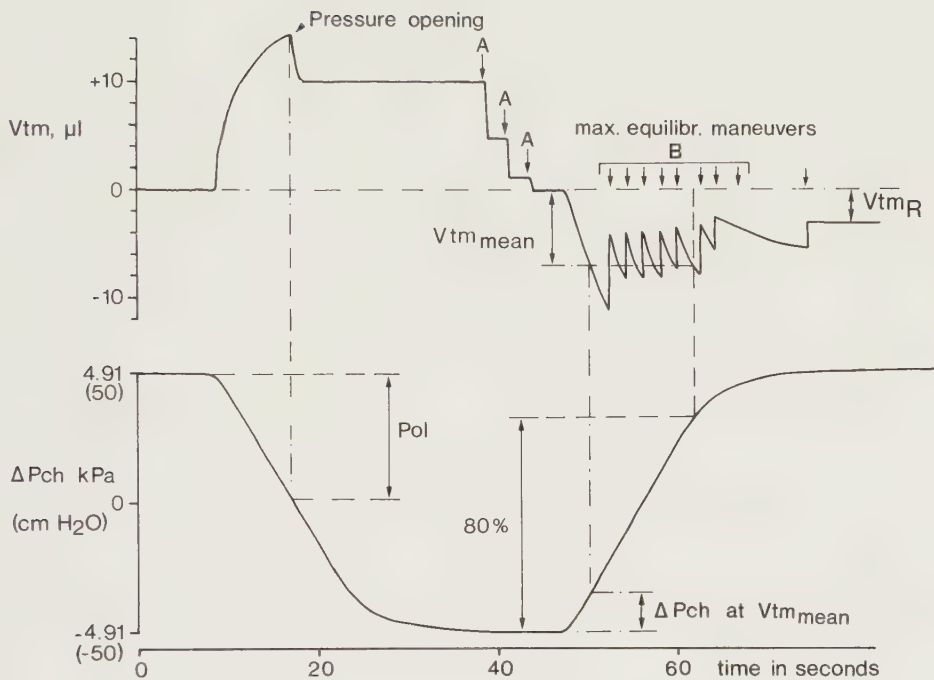


Fig. 1. Example of recording of ear drum displacement (V_{tm} in μl) in upper curve, and chamber pressure (P_{ch} in $cm H_2O$ or kPa) in lower curve. Pol indicates pressure opening level and V_{tmR} indicates eardrum displacement at residual pressure R.

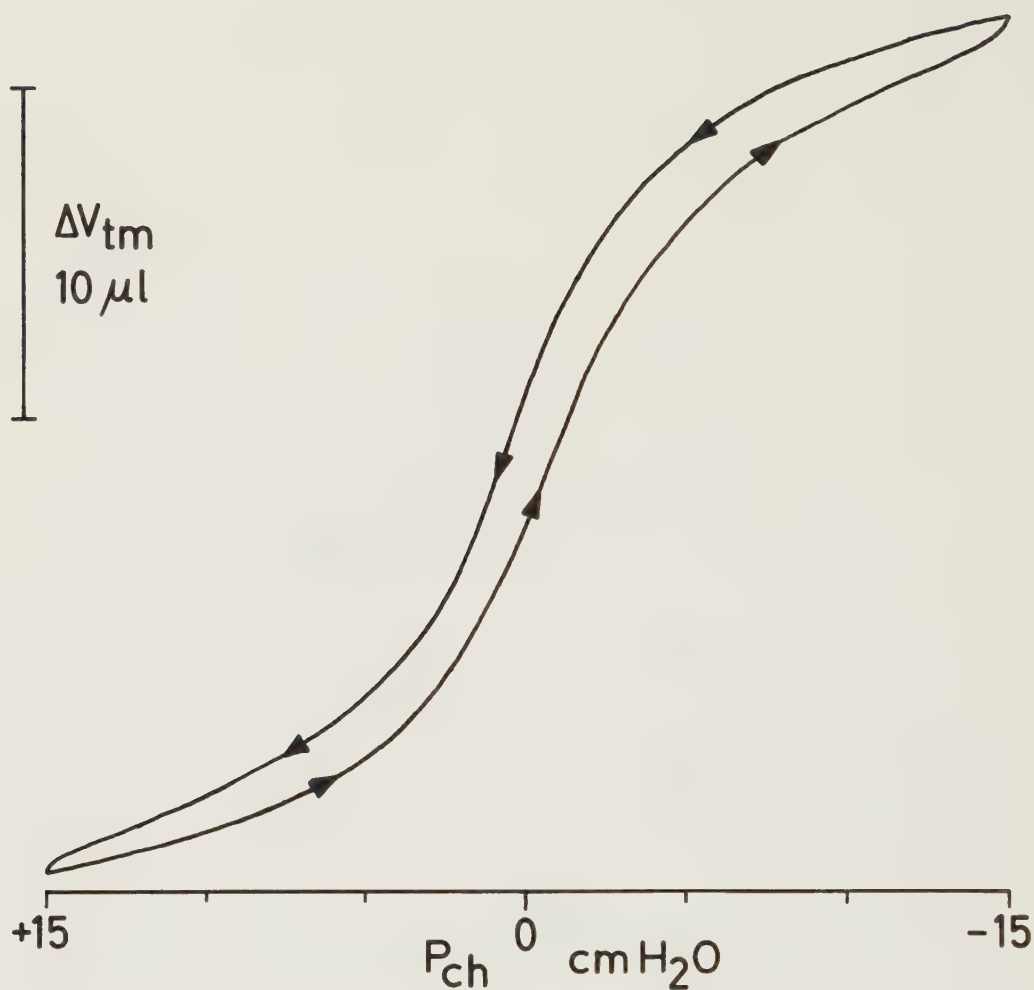


Fig. 2. Example of recording of the volume/pressure curve of the eardrum system. Different tracks of the curve in pressure increase and decrease depend on hysteresis.

training, was chosen partly to find out if the results in test 1 were reproducible and partly to find out if those with initially poor results had improved sufficiently to motivate further training. The time for test 3 was chosen after approximately another year of training in high performance jet fighters.

MATERIAL AND METHODS

In 2 earlier studies (8,9), 52 accepted applicants had passed a comprehensive test of the tubal function before primary flight training. 20 of these had to discontinue the following tests for various non-medical reasons. The remaining 32 subjects did not differ statistically from the original 52 as far as the results of the different first tests were concerned, and were therefore regarded as a representative sample. Their flight experience between test 1 and test 2 comprised about 150 hours in one year mostly in jet training planes. Between test 2 and test 3 the pilots had logged an average of 260 hours in jet fighters in regular military service. Audiography (within 20 dB ISO, 1964) and otomicroscopy including Siegle's test revealed nothing remarkable before tests and no one had a history or signs of a recent URI. All 3 tests were performed during the same time of the year, fall, with the same equipment and procedure, so as to keep external test conditions as constant as possible.

Using a pressure chamber and the method of Ingelstedt et al. (13) and Elnor et al. (5), the Eustachian tube pressure equilibrating capacity was studied. The principle of the method is to record the volume of air displaced by movements of the eardrum (V_{tm}) in response to changes in the ambient and intratympanic pressures as in ascent and descent (Fig. 1). The method also admits of studying the elastic properties of the eardrum system as a volume/pressure relationship, where this quotient is defined as the volume deviation of the eardrum from its neutral position (V_{tm}) as a function of a pressure load across the eardrum ($V_{tm} = f(P_{ch})$) (Fig. 2).

After an explanation of the purposes of the tests, instructions and demonstrations of Valsalva's and Toynbee's manoeuvres, the subject was placed in a convertible chair for recordings in first the seated and then the recumbent position. The tests were made in the following order:

1. Toynbee's and Valsalva's manoeuvres, 5 tries each, where a successful manoeuvre is indicated by a movement of the eardrum.

2. Active equilibration of static over- and underpressures of 10 cm H₂O in the middle ear, in the seated position only, using the method of free choice, i.e. deglutitions and/or jaw movements, to allow the distribution into Elner's tubal function groups (6).

Group I: Equilibrates completely.

Group II: Equilibrates with small residual over- and underpressures.

Group III: Equilibrates the overpressure like group II, but not the underpressure.

Group IV: Cannot equilibrate at all.

3. The mean pressure across the eardrum during simulated descent (P_{tm} mean) from -50 to +50 cm H₂O ($\pm$ 4.91 kPa) in 25 s. The subject was told to equilibrate as best he could using the method of free choice.

4. The residual pressure in the middle ear immediately after descent (R) measured as the percentage of the total pressure change in the chamber during descent.

5. The relative overpressure in the middle ear needed to force the tube open = the pressure opening level (Pol) during simulated ascent from +50 to -50 cm H₂O ($\pm$ 4.91 kPa). During this test the subject was not allowed to equilibrate.

6. The volume deviation of the eardrum (V_{tm}) was determined in response to chamber pressures of $\pm$ 15 cm H₂O in relation to the neutral position of the eardrum (Fig. 2).

For each variable the testing before the flight training will be referred to as test 1, and those after training as tests 2 and 3 respectively. The statistical evaluation of the results in the three tests for the variables Pol, P_{tm} mean, R and V_{tm}/ $\pm$ 15cm H₂O

was made by analysis of variance, and the differences between single tests were evaluated by the method of simultaneous confidence intervals (T-values). In order to find out if flight training leads to significant changes in single ears between tests in the different variables, the variation in repeated measurements, i.e. the total error of the method, must be known. The test-retest reliability of measurements of Pol, Ptm mean and R have been calculated in both ears of 25 subjects (10) and of $V_{tm}/\pm 15 \text{ cm H}_2\text{O}$ in 18 ears. The standard error of the differences between 2 measurements was for Pol 4.8 cm H₂O, for Ptm mean 4.3 cm H₂O, for R 11.3 % and for $V_{tm}/\pm 15 \text{ cm H}_2\text{O}$ 0.92 μl . Changes in results larger than the standard error in single ears over the whole test period, test 1-3, will be presented as improvements or deteriorations of tubal function.

RESULTS

All the subjects could perform the Valsalva manoeuvre except one who was unilaterally negative in both the seated and the recumbent position, and one who was unilaterally negative in recumbency, both of them in test 1. All were Valsalva positive in tests 2 and 3.

Table I. *Results of Toynbee's manoeuvre in single ears, a comparison between tests 1, 2 and 3.*

Test	Sitting			Recumbent		
	pos	neg	(pos %)	pos	neg	(pos %)
1	54	10	(84)	37	23	(62)
2	61	3	(95)	54	6	(90)
3	63	1	(98)	54	6	(90)

The results of Toynbee's manoeuvre are provided in Table I. There is an obvious improvement between tests, since of the 10 negative ears in test 1, 3 remained negative in test 2 and only 1 in test 3 in the seated position. Corresponding figures in recumbency were 23, 6 and 6 respectively. Only 2 ears turned negative in the seated and 3 in the recumbent position in tests 2 and 3.

Table II. *Distribution of single ears in tubal function groups by method of free choice in tests 1, 2 and 3.*

Test	I		II		III		IV	
	No	(%)	No	(%)	No	(%)	No	(%)
1	51	(80)	8	(13)	2	(3)	3	(5)
2	49	(77)	13	(22)	1	(2)	1	(2)
3	46	(72)	14	(22)	2	(3)	2	(3)

The results of active equilibration of static over- and under-pressures in the middle ear showed no significant difference between tests, $\chi^2 = 0.73$ n.s. in Friedman's test. As may be seen from Table II, 3 of the 5 ears in groups III and IV improved to groups I and II and no one deteriorated in test 2. However, in test 3, 2 of those who originally improved fell back to groups III and IV.

The results of active efforts to clear the ears by the method of free choice during simulated descent measured as Ptm mean are presented in Table III for the seated and in Table IV for the recumbent position. There is no significant change between tests in the seated position. 14 ears improved, and 10 deteriorated. In recumbency there was a significant improvement over the whole test period. 19 ears improved and 6 deteriorated. The residual pressure in the middle ear immediately after descent (R) was not changed significantly between tests in either body position. Results are given in Tables V and VI. 6 ears deteriorated in both positions, 10 improved in the seated and 16 in recumbent position.

Results of the pressure opening level (Pol) during simulated ascent are shown in Tables VII and VIII. There is a highly significant improvement (lowering of the Pol) between tests 1 and 2 in both body positions. 37 ears improved and 6 deteriorated in the seated position. 37 ears improved and 4 deteriorated in recumbency. Large Pol-values, in contrast to smaller, tend to be more reduced in the retests. In Figs 3 and 4 results are given in groups according to Pol-values in test 1 (Pol_1) compared with the results of the same ears in tests 2 and 3. However, the difference in results due to body position remains stable between tests indicating that this positional factor is not influenced by flight

Table III. *Ptm mean in cm H₂O in tests 1, 2 and 3 for single ears in the seated position. T-value for differences in single ears between tests.*

Test	No	$\bar{X}$	S.D.	S.E.M.	
1	61	13.47	13.38	1.67	$T_{1-2} = 0.790$ n.s.
2	54	11.56	11.77	1.51	$T_{2-3} = 0.668$ n.s.
3	57	11.81	10.71	1.42	$T_{1-3} = 1.458$ n.s.

Table IV. *Ptm mean in cm H₂O in tests 1, 2 and 3 for single ears in the recumbent position. T-value for differences in single ears between tests.*

Test	No	$\bar{X}$	S.D.	S.E.M.	
1	57	19.57	14.73	1.94	$T_{1-2} = 2.184$ n.s.
2	59	16.60	12.79	1.61	$T_{2-3} = 1.025$ n.s.
3	54	15.86	12.14	1.58	$T_{1-3} = 3.209^{xx}$

Table V. *Results of R in % of the total pressure change in descent in tests 1, 2 and 3 for single ears in the sitting position. T-values for differences in single ears between tests.*

Test	No	$\bar{X}$	S.D.	S.E.M.	
1	61	17.87	33.25	4.22	$T_{1-2} = 0.63$ n.s.
2	56	12.14	33.25	3.36	$T_{2-3} = 1.10$ n.s.
3	55	9.40	22.26	2.95	$T_{1-3} = 1.70$ n.s.

Table VI. *Results of R in % of the total pressure change in descent in tests 1, 2 and 3 for single ears in the recumbent position. T-values for differences in single ears between tests.*

Test	No	$\bar{X}$	S.D.	S.E.M.	
1	57	33.45	42.30	5.56	$T_{1-2} = 0.92$ n.s.
2	58	29.65	38.44	4.84	$T_{2-3} = 0.56$ n.s.
3	53	26.00	35.11	4.57	$T_{1-3} = 1.48$ n.s.

Table VII. Pol in cm H₂O in tests 1, 2 and 3 for single ears in the seated position. T-values for differences in single ears between tests.

Test	No	$\bar{X}$	S.D.	S.E.M.	
1	60	47.08	18.86	2.56	$T_{1-2} = 7.097^{xxx}$
2	60	33.55	16.14	2.08	$T_{2-3} = 0.367$ n.s.
3	60	32.85	18.34	2.37	$T_{1-3} = 7.464^{xxx}$

Table VIII. Pol in cm H₂O in tests 1, 2 and 3 for single ears in the recumbent position. T-values for differences in single ears between tests.

Test	No	$\bar{X}$	S.D.	S.E.M.	
1	58	58.57	19.25	2.53	$T_{1-2} = 4.783^{xxx}$
2	58	47.93	16.24	2.13	$T_{2-3} = 0.543$ n.s.
3	58	46.72	17.33	2.27	$T_{1-3} = 5.325^{xxx}$

Table IX. Comparison of the volume/pressure relationship of the drum in tests 1, 2 and 3 for single ears in the seated position. T-values for differences in single ears between tests.

Test	No	$\bar{X}$	S.D.	S.E.M.	
1	59	28.31	± 5.64	0.78	$T_{1-2} = 2.96^{xx}$
2	53	29.46	± 5.56	0.77	$T_{2-3} = 7.52^{xxx}$
3	57	32.65	± 6.08	0.84	$T_{1-3} = 10.238^{xxx}$

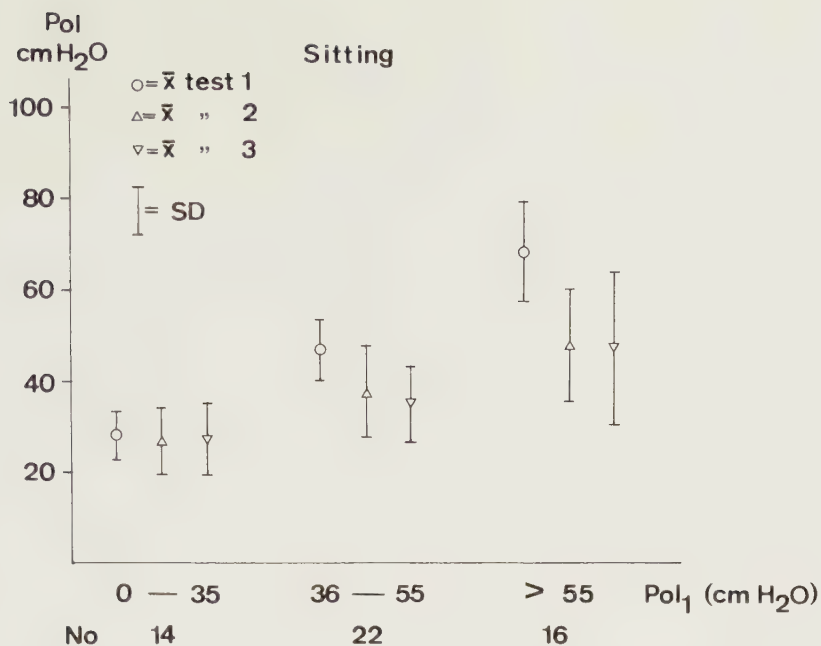


Fig. 3. Distribution in groups of Pol according to results in test 1 (Pol₁) in single ears in the seated position in comparison with the same ears in tests 2 and 3.

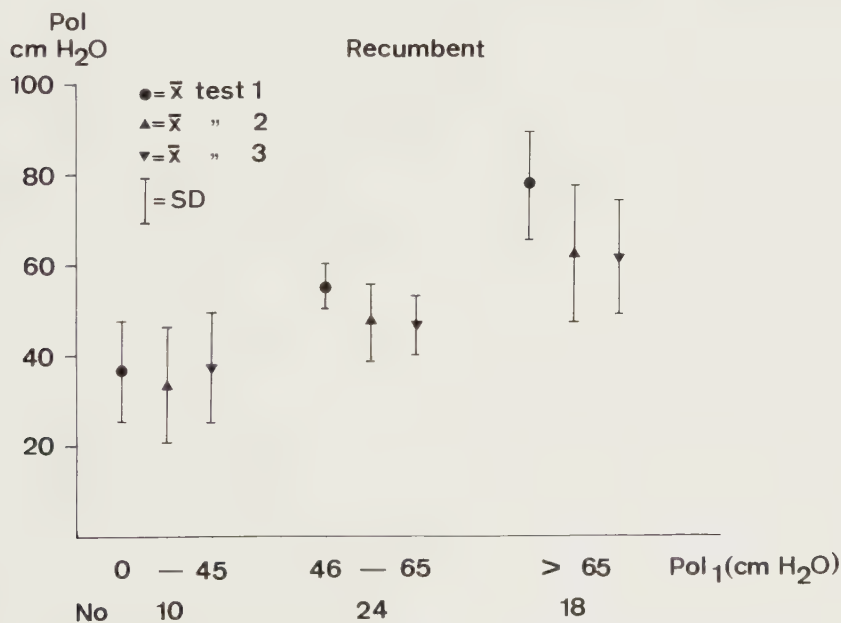


Fig. 4. Distribution in groups of Pol according to results in test 1 (Pol₁) in single ears in recumbency in comparison with the same ears in tests 2 and 3.

training.

The volume deviation of the drum in response to changes in ambient pressure, $V_{tm}/\pm 15 \text{ cm H}_2\text{O}$, was significantly increased between tests. 56 % of the ears increased and only 2 % deteriorated. Results are given in Table IX. All 64 ears investigated were not rendered account for in the results. 8 ears had tuba aperta at one or more recordings that made it impossible to establish necessary pressure differences across the eardrum. In a few subjects the Pol was not as distinct as in the recording example (Fig. 2) due to a leaking behaviour of the tube that made accurate calculation impossible. Artefacts from jaw movements that changes the position of the catheter in the ear canal have ruined some recordings of P_{tm} mean and R and in 2 cases there has been leakage from the catheter in the ear canal that has made proper recordings impossible.

DISCUSSION

In an attempt to evaluate the tubal function, it is convenient to make a distinction between tests measuring the passive function and tests measuring the active function. Valsalva's manoeuvre and Pol represent passive function and Toynbee's manoeuvre, static pressure equilibration, P_{tm} mean and R represent active function. A change in $V_{tm}/\pm 15 \text{ cm H}_2\text{O}$ between tests is supposed to reflect the sum of loads on the eardrum depending upon the degree of both passive and active function of the tube. Since applicants for flight training invariably are reputed to be alert and anxious to do their best, we do not think that differences in this respect between tests have influenced the outcome of the active function tests.

Since the Valsalva manoeuvre is only recorded qualitatively and almost every ear was positive already at test 1, it is not possible to register any improvements. The Pol, measuring the total tubal closing forces, was significantly lowered above all between tests 1 and 2. In order to investigate this finding further, 10 ears with a large reduction of Pol between tests were chosen, and the pressure closing levels (P_{cl}) were calculated from the original recordings of Pol. P_{cl} is defined as the residual overpressure in the middle ear, when the tube closes after the pressure opening during ascent (6). The difference between

Pol and Pcl illustrates the intraluminal portion of the total tubal closing forces, i.e. viscosity and surface tension of the mucus and the blood content of the mucous membrane (12). Results of Pcl for the whole material are not shown, since only in a limited number of ears, recordings were distinct enough to allow an accurate calculation. The decrease of Pcl between tests was of the same magnitude as that of Pol, indicating that the difference, the intraluminal portion of the closing force, is stable and not affected by flight training. Therefore the decrease in Pol and Pcl rather reflect a change in the elastic properties of the tubal and peritubal tissues, presumably the cartilage. This lowering of Pol may be significant in reducing the risks for alternobaric vertigo during ascent and could be seen in contrast to Tjernström's (17) very stable results of Pol at repeated recordings in subjects not exposed to ambient pressure changes. An applicant with initially high Pol involving risks of alternobaric vertigo should therefore not be disqualified automatically, but reevaluated after primary flight training. Just as Ivarsson et al. (15) showed that divers exposed to ambient pressure changes have greater mobility of the eardrum system as compared to non-divers, we find increased $V_{tm}/^{+} 15 \text{ cm H}_2\text{O}$ after flight training, n.b. in the same subjects. However, subjects with $\text{Pol} < 28 \text{ cm H}_2\text{O}$ (Pol mean - 1 SD) in the seated position at test 1 had no significant increase in V_{tm} as compared to the rest of the material with higher Pol where a highly significant increase in elasticity of the eardrum system was found. These findings may indicate that high but not low Pol load the drum enough to cause an increase in $V_{tm}/^{+} 15 \text{ cm H}_2\text{O}$. We find no similar relation between V_{tm} and different degrees of negative pressure in the middle ear during descent. Even subjects with minimal load of the drum during descent had significant increase of V_{tm} between tests.

All subjects changing to positive in the Toynbee manoeuvre had a significant lowering of Pol. Since Pol is the measure of the closing forces that have to be overcome in Toynbee's manoeuvre, the improvement may well be explained by this lowering. It is not likely that the improvement is caused by better muscular function in deglutition, since a corresponding improvement in the active equilibration measured as P_{tm} mean is not found in more

than 5 of the 9 ears in the seated and 7 out of the 17 in the recumbent position. Corresponding figures for the improvement in active equilibration measured as R were 2 of the 9 ears in the seated and 5 of the 17 ears in the recumbent position. Friedman's test showed no significant differences in the results of static pressure equilibration between tests. Most of the changes were within groups I and II, good function, and no ear deteriorated to groups III and IV, bad function. In the simulated descent tests significant improvement was only found for Ptm mean in recumbency, which may be attributed to the greater sensitivity of this test position. It is throughout a feature of this study that improvement is found in the passive function of the Eustachian tube.

The validity of the test results should be in a good agreement with the results of the actual flight training, but one must bear in mind that the rates and amounts of pressure change in the tests, for practical and ethical reasons, are not nearly as high as in flight. It is a common opinion that the higher rates and amounts of ambient pressure change the more difficult is pressure equilibration. Andréasson et al. (1) showed that Pol increases with higher rates of ambient pressure reduction, but investigations with ambient pressure increase as in descent are not reported. However, Dickson and King (4) have reported a threefold increase in the incidence of aerotitis media in air crews in jet planes as compared to piston-engined aircraft, the increase being attributed to the higher prestanda in ascent and descent of jet planes. The same factor is also indicated by the well-known fact that increasing pressure difference across the Eustachian tube during descent makes it more difficult to clear the ears. In subjects who had a residual pressure of more than 50 % after descent in the seated position all but 1 are known from the medical interview to use the Valsalva manoeuvre every now and then, especially during rapid descents. Some of the pilots that exhibit an inconstant tuba aperta during the tests say that they can open the tube intentionally to equilibrate, but cannot explain how they do it. Possibly this tuba aperta is achieved by muscular function other than deglutition and/or jaw movements. There seems to be no way of finding a subject with ear trouble large enough to affect his capacity as a pilot unless he makes a report, which as shown by experience, is not likely. US Air Force does not require barotrauma to be reported as a physiological incident unless it is

incapacitating (16). This is obvious if a mission has to be interrupted, but it can also be completed at a very low qualitative level because of otitic barotrauma, and therefore not reported.

The retests have on the whole confirmed the results of test 1. Changes in results between tests are mostly to the better. The risk of picking an aspirant with poor tubal function for flight training because of a temporarily good test result seems negligible. The retests have also confirmed that it is not possible to pick the desirable applicants who can clear the ears without trouble during simulated descent by their results in simpler tests of the tubal function. Therefore, the pressure chamber technique with a quantitative measurement of the pressure equilibrating capacity of the Eustachian tube seems indispensable for a proper selection procedure.

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RELIABILITY IN TESTS OF THE EUSTACHIAN TUBE FUNCTION

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Key words. Eustachian tube function, Test-retest reliability

Abstract. With the aid of a quantitative impedance method and a pressure chamber, the capacity of the Eustachian tube to equilibrate pressure differences across the tympanic membrane was repeatedly determined in 20 otologically healthy men. The test-retest reliability was calculated from 5 determinations of static pressure equilibration of over- and underpressures of 10 cm H₂O and 10 determinations of equilibration of dynamic pressure changes. The pressure opening level of the tube during pressure increase in the middle ear was significantly lowered in the initial determinations. The residual pressure in the middle ear after maximum equilibrating efforts during pressure increase in the chamber was also significantly lowered. For the rest, the test-retest reliability was good. Ears with perfect tubal function had better test-retest reliability for all parameters tested than ears with poorer function. The significance of repeated measurements and the value of reliability determinations are discussed.

INTRODUCTION

Just as flying and diving require proper tubal function, so does reconstructive ear surgery. The selection of candidates for either purpose calls for tubal function tests. However, the prognostic value of such tests has not been convincing. One reason for this is of course that there are other causes for failure. Another reason may be improper testing. Many tubal function tests have been criticised for not being physiological, or else for only reflecting the tubal function at the moment of testing.

The reliability of a method to test the tubal function may be defined as the ability to yield more or less similar - preferably identical - results upon repeated measurements of the same subject. Variations in the results are the sum of variations in the performance and handling of instruments and the test subject, and are based on the standard deviation of the single measurement. Measurements should obviously be made at the same session to minimize influence of irrelevant external factors. The test-retest reliability of the results must be known for evaluation of changes in tubal function, i.e. in pharmacological studies. Tests of reproducibility have been presented earlier, but usually only from 2 consecutive recordings and the results have been presented in rather vague terms. The time elapsed between recordings has varied from a few minutes to several months. However, Holmquist (1969a) reported 80 % reproducibility within ± 1.5 cm H₂O after equilibration of +20 cm H₂O in 85 ears and in 65 % after equilibration of -20 cm H₂O in 101 ears, all with dry chronic otitis media. Using sonotubometri in 72 normal ears, Virtanen (1977) found reproducibility in sound transmission within 5 dB in about 80 %. Using the microflow method in a pressure chamber, Ingelstedt et al. (1974) tested the passive pressure opening function of the Eustachian tube during dynamic pressure increase in the middle ear in 18 normal ears repeatedly in repeated sessions. The standard deviation of the pressure opening level in repeated measurements in single ears within sessions was 3.6 cm H₂O and between sessions 4.4 cm H₂O.

Reports of changing tubal function during repeated measurements (Naunton & Galluser, 1967; Cantekin et al., 1976; Groth et al., 1981) and the need for comparative studies have thus focused our interest on the question of the reliability of

different tubal function tests. The aim of this investigation was to study the Eustachian tube function in repeated measurements and to establish a measure of the reliability in recordings of various parameters of the pressure equilibrating capacity.

MATERIAL

The material consisted of 20 men aged 19-24, mean 21. All were otologically healthy when tested by otomicroscope including Siegle's test and audiography (within 20 dB ISO, 1964). No one had a history or signs of a recent upper respiratory tract infection.

METHOD

The main principle of the method is a continuous recording of changes in the tympanic membrane compliance in relation to maximum compliance during changes in middle ear pressure as well as during ambient pressure changes. An outline of the equipment is provided in Fig. 1. A pressure mini-chamber was constructed to induce ambient pressure changes. Technical data and a description of the chamber are given by Ivarsson et al. (1981). Determination of changes in the compliance of the tympanic membrane is made by a new impedance meter (Fig. 1). This new device has a servosystem which keeps a constant sound pressure level in the external ear canal independently of changes in ambient or intratympanic pressure. By means of a calculating unit, the enclosed volume of the external ear canal and the changes in volume, caused by changes of the tympanic membrane compliance, are calculated and from this recording it is possible to isolate the tympanic membrane compliance.

The impedance meter is calibrated by 2 airtight syringes which can be adjusted for different test volumes. The pressure transducer systems were calibrated by a water manometer. The reliability of volume and pressure recordings as well as the zeroline drift for each parameter have been checked during 5 days. The tests showed a reliability of calibration $\pm$ SD for recordings of volume ($V = 1000 \mu\text{l} \pm 9$) with a zeroline drift of $\pm 6 \mu\text{l}$; for chamber pressure recordings ($P_{\text{ch}} = 400 \text{ cm H}_2\text{O} \pm 4$) with a zeroline drift of $\pm 0.5 \text{ cm H}_2\text{O}$ and for recordings of pressure in the ear

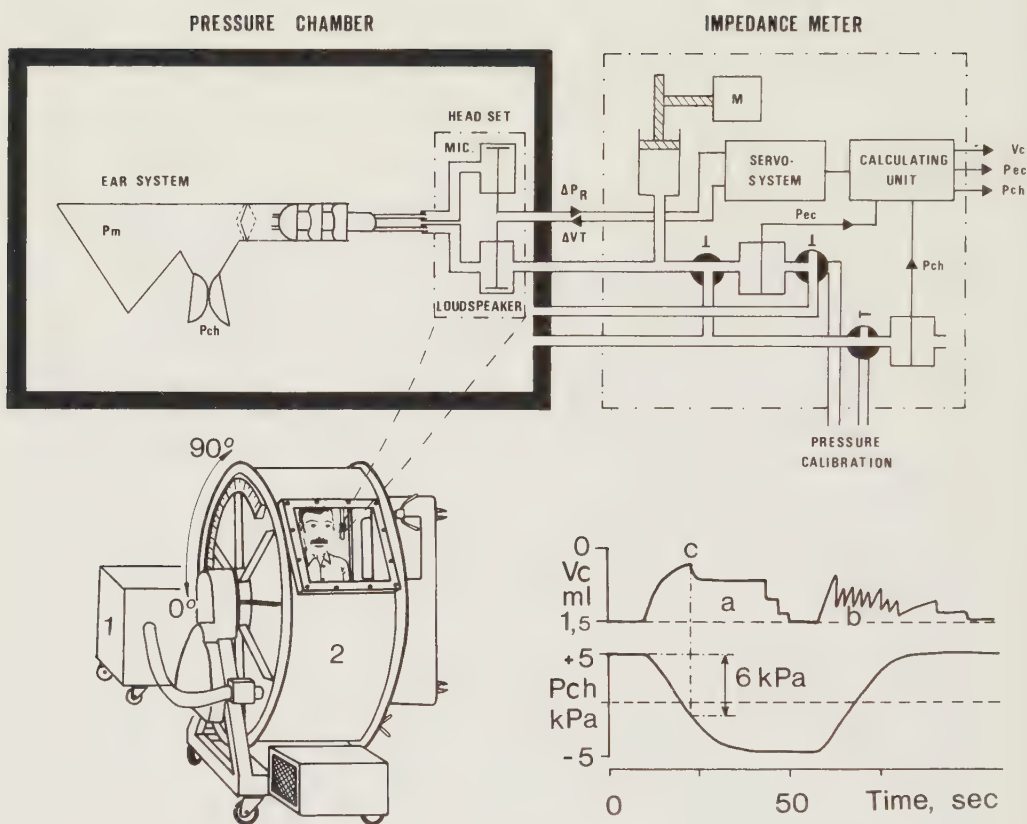


Fig. 1. Pressure chamber (1,2), servoregulated impedance meter including calculating unit used for recording of changes in eardrum compliance on ambient pressure changes. Recording example: Volume recording of eardrum compliance (V_c) in upper curve, on change of chamber pressure (P_{ch}) in lower curve, during ascent (a), descent (b) and pressure opening level at 6 kPa (c). Maximum compliance level recorded at 1.5 ml. A more detailed description of the equipment is provided by Ivarsson et al. (1981).

canal (Pec = 200 cm H₂O $\pm$ 0.3) with a zeroline drift of $\pm$ 0.2 cm H₂O.

PERFORMANCE

The test subject was seated comfortably in the pressure chamber, the test procedure was explained and instructions regarding the following tests were given.

1. Pressure opening equilibration during simulated ascent.

The pressure decrease necessary to induce a pressure opening (Pol) of the Eustachian tube was calculated as shown in Fig. 2. The chamber pressure was changed from +50 to -50 cm H₂O (+5 to -5 kPa). The test was repeated 10 times with intervals of up to 5 minutes. The subject was not allowed to equilibrate during the test.

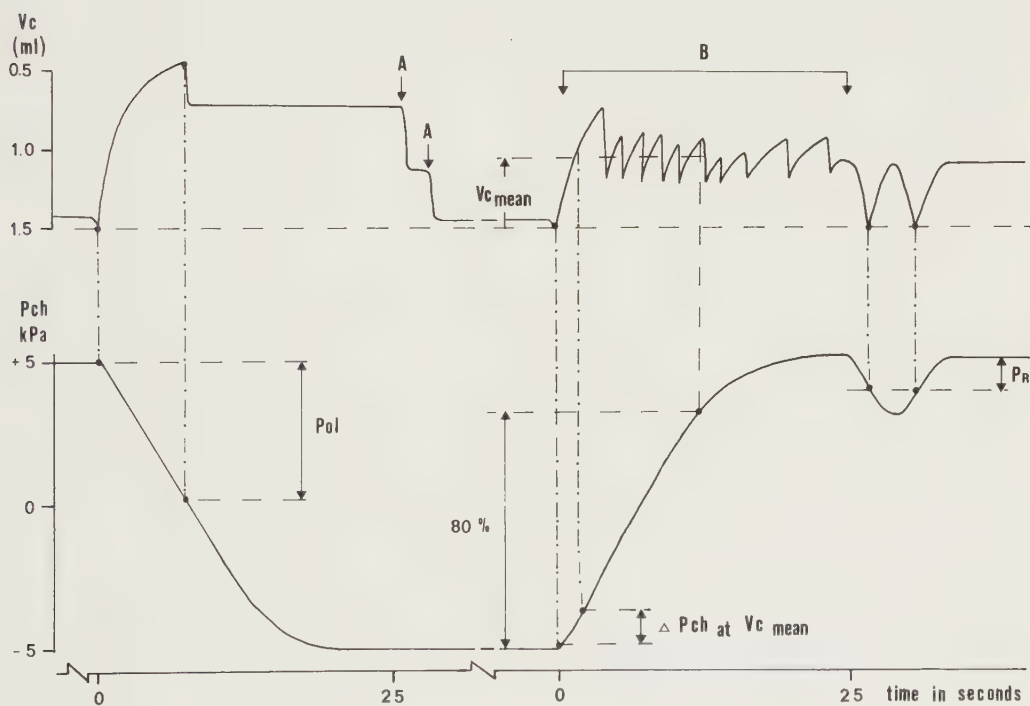


Fig. 2. Example of recording of volume of eardrum compliance (Vc) in ml and chamber pressure (Pch) in kPa. (A) indicates equilibrating manoeuvres after ascent. (B) indicates maximum equilibrating manoeuvres during descent. For details, see text.

2. Active equilibration during simulated descent.

Figure 2 also provides a recording example of the change in compliance of the tympanic membrane during pressure changes of 100 cm H₂O in 25 s. The rate of pressure change was constant during 80 % of the time. Vc mean denotes the mean deviation of the tympanic membrane compliance in relation to its maximum compliance, i.e. the neutral position of the tympanic membrane, during the constant phase of pressure increase. Vc mean was calculated planimetrically from the Vc curve. The pressure change needed to produce this Vc mean is derived from the Pch curve (ΔP_{ch} at Vc mean) and is called P_{tm} mean. It is a quantitative measure of the active equilibration capacity of the Eustachian tube.

3. Residual pressure in the middle ear after maximum equilibration efforts during simulated descent.

The residual pressure in the middle ear (P_R) was recorded by tympanometry immediately after the pressure change was finished and is also used as a measure of the equilibrating capacity. P_R is measured as percentage of the total pressure change in the chamber during descent, see Fig. 2.

4. Active equilibration of static pressure differences across the tympanic membrane.

After an increase or decrease of chamber pressure by 10 cm H₂O, the subjects were allowed to equilibrate the middle ear pressure by 10 deglutitions or jaw movements within 3 minutes. As may be seen in Fig. 3 a change in chamber pressure of 10 cm H₂O (1 kPa) induces a change in compliance of the tympanic membrane. The equilibrating capacity can be assessed in the stepwise increase in the recorded compliance towards its maximum value. The resultant residual pressure in the middle ear was calculated by tympanometry indicating maximum compliance of the tympanic membrane during changes in chamber pressure. The test was repeated 5 times with intervals of up to 5 minutes.

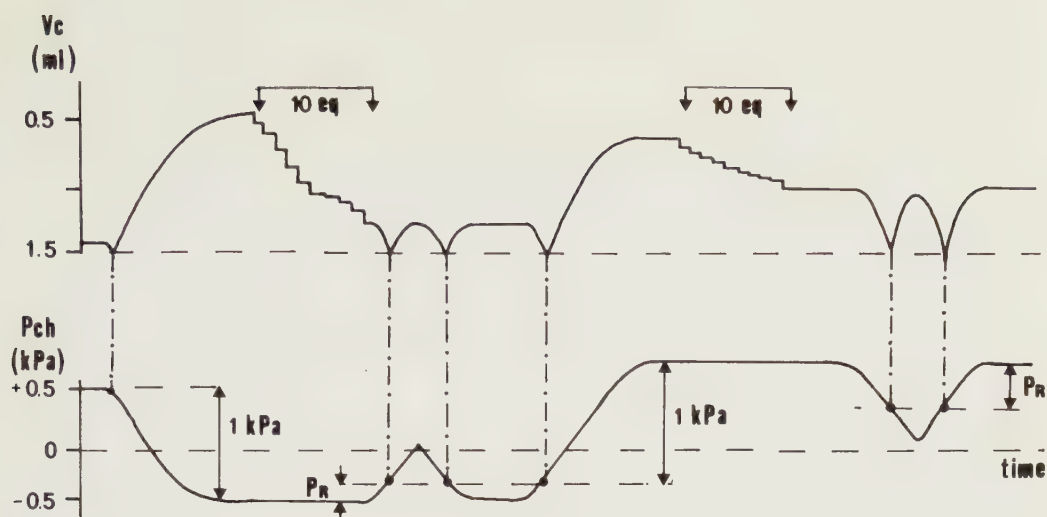


Fig. 3. Recording example of determination of residual pressures after equilibration of -1 and $+1$ kPa. 1 kPa ≈ 10 cm H_2O . 10 equilibrating manoeuvres were allowed (10 eq.).

RESULTS

1. Reliability of measurements of the pressure opening level (Pol)

Thirtyeight ears in 20 subjects were measured 10 times with intervals of up to 5 minutes. The pooled estimate of the variance of the pressure decreases which are necessary to induce the pressure opening of the tube was computed by first calculating the variance of the 10 measurements for each ear and then the mean variance for all 38 ears. The standard deviation for Pol calculated in this way was 3.55 cm H_2O and is the measure of test-retest reliability. The mean values of Pol for all ears at each measurement were calculated. Results are provided in Table I. Differences between mean values in the measurements were tested by the 2-way analysis of variance. The differences between all 10 measurements were highly significant, between measurement 1-4 significant, and between measurements 5-10 not significant.

Table I. *Pressure opening level (Pol in cm H₂O during chamber pressure decrease; mean and S.E.M. of 38 ears in 10 measurements.*

	all	1	2	3	4	5	6	7	8	9	10
Mean	36.58	39.60	37.58	35.88	37.69	36.46	36.13	35.78	35.04	35.46	36.00
S.E.M.	0.86	2.87	2.17	2.75	2.85	2.76	2.93	3.17	2.53	2.55	2.92

Table II. *Mean pressure across the tympanic membrane (P_{tm} mean in cm H₂O) during pressure increase; mean and S.E.M. of 37 ears in 10 measurements.*

	all	1	2	3	4	5	6	7	8	9	10
Mean	8.17	9.44	8.68	7.75	7.71	7.50	7.92	8.38	8.58	7.08	8.58
S.E.M.	0.40	1.58	1.58	1.11	1.11	1.20	1.24	1.10	1.29	1.14	1.40

Table III. *The residual pressure in the middle ear immediately after pressure increase (P_R) in % of the total pressure change; mean and S.E.M. of 37 ears in 10 measurements.*

	all	1	2	3	4	5	6	7	8	9	10
Mean	11.43	15.00	19.57	13.69	11.41	11.16	11.38	7.97	8.41	7.28	8.97
S.E.M.	1.20	4.51	5.32	4.10	3.64	3.54	4.21	3.12	3.15	2.58	3.20

Table IV. *Residual pressures in the middle ear after equilibration of static over- and underpressures of 10 cm H₂O; mean and S.E.M. of 38 ears in 5 measurements.*

		all	1	2	3	4	5
+10 cm H ₂ O	Mean	0.83	0.56	0.66	1.02	0.88	1.05
	S.E.M.	0.15	0.26	0.27	0.41	0.33	0.37
-10 cm H ₂ O	Mean	0.97	0.97	1.25	0.89	0.92	0.84
	S.E.M.	0.16	0.35	0.44	0.35	0.36	0.31

2. Reliability of measurements of the average pressure difference across the tympanic membrane during pressure increase (P_{tm} mean) and
3. The residual pressure in the middle ear immediately after increase (P_R)

Thirtyseven ears in 20 subjects were measured 10 times with intervals of up to 5 minutes. Using the calculating method described, the standard deviation for P_{tm} mean was 2.78 cm H_2O and for P_R 10.79 % of the total pressure change. The mean values for P_{tm} mean and P_R for all ears and each measurement are shown in Tables II and III. Differences in results between the 10 measurements of the P_{tm} mean were not significant, but for P_R there was a highly significant difference. However, for the first three measurements, and the seven last measurements, judged separately, the differences were not significant, indicating a change and stabilisation in this function after the first 3 measurements.

4. Reliability of measurements of the static pressure equilibrating capacity

Thirtyeight ears in 20 subjects were measured 5 times with intervals of up to 5 minutes (Table IV). The residual pressure in the middle ears after 10 deglutitions and/or jaw movements at relative over- and underpressures of 10 cm H_2O was recorded. Using the calculating method, the standard deviation of residual pressures after equilibration of overpressures was 0.95 cm H_2O and for underpressures 0.88 cm H_2O . The differences between measurements were not significant for either over- or underpressures.

DISCUSSION

Repeated pressure openings result in lower values of Pol. This phenomenon has been observed by Cantekin et al. (1976) in repeated measurements of Pol in children. The lower value of Pol in the second measurement was possibly due to changes in the surface tension and maybe to other qualities of the mucus in the tubal lumen caused by the first pressure opening. The same observation has been made by the present authors in applicants accepted for flight training (Groth et al., 1981). In our measurements a steady state seems to appear after the initial four

pressure openings. Despite this change the standard deviation is only 3.55 cm H₂O. There is no difference in reliability of high or low values of Pol. If the initial 4 values of Pol are omitted, as settling values, the standard deviation will be even smaller and the reliability in the measurements increased. Test-retest reliability measurements of the passive dynamic pressure equilibration function have only been reported by Ingelstedt et al. (1974). They used a microflow method, but otherwise the tests were identical. Comparative measurements of tubal function using the microflow method and this impedance method provided no significant differences (Groth et al., 1981). The result of Ingelstedt et al. (1974) of variation within sessions (3.6 cm H₂O) is also very close to our result 3.55 cm H₂O. The residual pressure in the middle ear immediately after pressure increase also showed falling values in the 3 first measurements. Since this test was made after the pressure opening test, the tube had already been forced open several times and it is not likely that changes in the mucus could explain the falling values of P_R. However, it is possible that the rather intensive muscular activity in the tube during this test affects the blood content in the mucus membranes lining the tubal lumen so as to facilitate pressure equilibration. Naunton & Galluser (1967) found sonometric indications of increasing admittance of sound through the tube during repeated swallowing.

The standard deviation of P_R is considerably greater than for the other parameters studied. This is partly caused by the 12 ears with residual pressure above 5 % since the standard deviation is 17.19 % as compared to 2.77 % for the remaining ears. This means that ears with good equilibrating capacity have a stable function as compared to ears with poorer capacity, which mix good and poor performance as indicated by the larger standard deviation. The reason for this variation may be that the difference between a good and a poor result lies in a single successful equilibration more or less. The other variable studied under pressure increase (P_{tm} mean) showed no tendency to change between measurements. Its standard deviation for ears with P_R ≤ 5 % was 2.63 cm H₂O and 4.15 cm H₂O for ears with P_R > 5 %, indicating good reliability irrespective of the residual pressure. The very small standard deviations in the measurements of the static pressure equilibra-

tion tests merely show that it is simple compared to the dynamic pressure tests. Only 5 ears had a mean residual overpressure of more than 1 cm H₂O and 6 ears had a mean residual underpressure of more than 1 cm H₂O. For these 11 ears the standard deviation was 2.27 cm H₂O for overpressures and 1.85 cm H₂O for underpressures. For the remaining ears with residual pressures of 1 cm H₂O or less, the standard deviation for overpressures was 0.39 and for underpressures 0.34 cm H₂O. Holmquist (1969b) reported a difference of less than 1 cm H₂O in 2 measurements of equilibration of static underpressures of 10 - 25 cm H₂O in the middle ears in 18 out of 20 normal ears.

These measures of reliability may be used for future comparative studies in normal ears using the quantitative impedance method, in order to find out if a difference in results between measurements is significant or not. N.b. for this purpose the variance must be multiplied by 2 since 2 measurements are involved in the comparison. The dynamic pressure equilibration tests used in this study seem suitable for comparative tests, in contrast to static pressure equilibration tests where normal subjects can to a great extent equilibrate completely.

It is a common objection to tubal function tests that they only reflect the function at the moment of testing. Apart from the variation in the initial measurements of P_{ol} and P_R , the results in this study seem to contradict such a statement. The new impedance method provides a quantitative measure of the pressure equilibrating capacity of the Eustachian tube with high precision for static as well as dynamic pressure changes.

ZUSAMMENFASSUNG

Die Fähigkeit der Tuba Eustachii, Druckunterschiede zwischen der Pauke und der Umgebung auszugleichen, wurde an 20 Männern mit gesunden Ohren mit Hilfe einer quantitativen Impedanzmethode in einer Druckkammer wiederholt geprüft. Die Reliabilität der Messwerte bei wiederholten Untersuchungen wurde berechnet. Dies geschah an Hand von fünf Messungen des Druckausgleiches bei statischen Druckunterschieden von ± 10 cm H₂O und von zehn Messungen des Ausgleiches bei dynamischen Druckveränderungen. Der Druckwert, bei dem sich die Tube bei Drucksteigerung im Mittelohr öffnete, war bei den anfänglichen Messungen signifikant verringert. Signifikant verringerte Messwerte ergaben sich auch bei Registrierung des Restdruckes im Mittelohr nach maximalen Druckausgleichsanstrengungen bei ansteigendem Druck in der Kammer. Bei den übrigen Versuchen wurde bei Wiederholung eine zufriedenstellende "Übereinstimmung festgestellt. Ohren mit vorzüglicher Tubenfunktion wiesen bei wiederholten Versuchen eine bessere "Übereinstimmung betreffs sämtlicher geprüfter Parameter auf, als Ohren mit weniger guter Funktion. Die Bedeutung wiederholter Messungen und der Wert von Reliabilitätsbestimmungen werden diskutiert.

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